COLLEGE OF ENGINEERING, MATHEMATICS AND PHYSICAL SCIENCES

Event Management and Event Response Planning for Smart Water Networks

Submitted by Eirini Nikoloudi to the University of Exeter
as a thesis for the degree of
Doctor of Philosophy in Water Informatics Engineering
in October 2020

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: ……………………………………………………………..

ABSTRACT

The water industry in the UK and worldwide has a pressing need to better manage interruptions to water supply caused by various failure events, such as pipe bursts, equipment failures or water treatment work shutdowns. One way of doing this is by making use of the increasingly available real-time sensor data collected in water distribution systems, as well as by using hydraulic models in real-time. Currently, real-time sensor data and real-time hydraulic modelling are not used much in a water utility's control room, especially when it comes to identifying a suitable strategy to respond to failure events in near real-time.

This PhD project aims to develop, test/validate and demonstrate a new response methodology to support decisions made by control room operators when dealing with various failure events in a water distribution system. An integral part of this work is to develop an interactive decision-support tool, which will guide/support operators in identifying an effective response solution in near real-time (i.e. usually required up to 1 hour after the event detection/localisation if unforeseen events in the field are not considered). The tool will be used in this thesis to test and validate the response methodology. The proposed response methodology considers: (i) structured yet flexible approach supporting and guiding the operator throughout the entire response process to water network failure events, whilst allowing the operator to have a final say; (ii) novel interaction with the operator in near real-time via the proposed tool (e.g. allowing operators to propose different 'what-if' scenarios without being hydraulic experts); (iii) provision of automatically generated advices (e.g. near optimal response solutions via a novel heuristic algorithm and assessed end-impacts); and (iv) improved impact assessment. An integral part of the response methodology is the development of a novel method to identify near optimal response to failures in water distribution networks. The response problem is formulated as a two-objective optimisation problem with objectives being the minimisation of failure impacts and related operational costs. The heuristic-based method is developed and used to solve this problem. For the first objective (i.e. impact assessment), a new impact assessment method is developed, using realistic impact indicators that cover different aspects of the event - which are consistently calculated for every proposed response solution (to facilitate easy comparison between different response solutions).

The response methodology was tested, validated and demonstrated on a semi-real case study. The implementation of the response methodology via the tool enabled operators to identify a response solution better (i.e. with lower end-impact and cost) than the solution based on the current response practice of utilities. The results obtained from this case study, demonstrate that the response methodology works well and that it has a potential to improve water utilities' current practice. The heuristic optimisation method that is integral part of the response methodology was validated and demonstrated on two semi-real case studies. Based on the results obtained it can be concluded that the heuristic-based method works well (i.e. it is reliable and robust) and is able to identify near optimal response solutions in a computationally fast manner. This, in turn, enables this method to be used in near real-time in real-life situations.

ACKNOWLEDGEMENTS

Coming to the end of my PhD programme, I feel the need to express my gratitude to the people who joined me in this long journey.

Firstly, I would like to express my deepest gratitude to my first academic supervisor, Professor Zoran Kapelan, who gave me the opportunity to take part in the WISE Centre for Doctoral Training in the University of Exeter. Apart from supervisor, he was my mentor as well, and his continuous guidance, support and encouragement made this journey easier and more productive. I am also very grateful to my second academic supervisor, Professor Fayyaz Memon, whose support and encouragement were significant during this journey.

My special thanks go to my industrial supervisor, Dr Michele Romano from United Utilities (UU). Michele’s deep expertise and love for his work inspired me to complete a big part of this thesis. His contribution was determining for the accomplishment of this thesis.

I would like to express my gratitude to the WISE community and the Centre of Water Systems of the University of Exeter, who created an inspiring and interactive environment to work in and helped me adapt easily to the new environment and make new friends.

I would also like to acknowledge the significant contribution of the people from UU. More specifically, my special thanks go to Mr Kevin Woodward, Mr Terry Chapman, Mr Tom Allen, Mr Ian Mercer, Mr Mario Pacheco, Mr Lloyd Chikuruwo, Mr Michael Haworth, Mr Andrew Hankinson, Mr Michael Rooney, Ms Sally-Anne Flanagan, Ms Devina Naga, Ms Laura Conroy, Ms Leah Milsom and Ms Lucy Cheng. This thesis could not have been completed without their support, as they provided a big amount of data for my case studies and guided me with patience through many of the UU processes required for this work.

My special gratitude goes to my beloved parents, brother and sister. Their continuous support and love helped me overcome many obstacles during this journey. My thanks extend to my close friends, who were by my side during the last demanding 4 years, as well as to a special person in my life who although joined me in this journey at the end, he made it easier.

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LIST OF ABBREVIATIONS

AEM	Abnormal Event Management
AMC	Alarm Management Centre
ASV	Alternative Supply Vehicle
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AMLP	Average Minutes Low Pressure
B&B	Branch-and-Bound
BFS	Breadth-First-Search
CV	Check Valve
CMP	Critical Metered Point
CML	Customer Minutes Lost
DSS	Decision Support System
DST	Decision Support Tool
DFS	Depth-First-Search
DRI	Discolouration Risk Increase
DPA	Discrete Pressure Area
DMA	District Metered Area
DWI	Drinking Water Inspectorate
EWDS	Early Warning Detection System
EWS	Early Warning System
EA	Environment Agency
ERS	Event Recognition System
EPR	Evolutionary Polynomial Regression

EPS	Extended Period Simulation
FCV	Flow Control Valve
FIC	Forward Incident Controller
GA	Genetic Algorithm
GIS	Geographical Information Systems
GRA	Global Resilience Analysis
ICT	Information and Communications Technology
ICC	Integrated Control Centre
IRPT	Interactive Response Planning Tool
IoT	Internet-of-Things
IMM	Intervention Management Model
JDL	Joint Directors of Laboratories
LP	Low Pressure
MOGA	Multi-Objective Genetic Algorithm
NSGA II	Non-dominated Sorting Genetic Algorithm (type II)
OWA	Ordered Weighted Averaging
OLB	Overland Bypass
PI	Performance Indicator
PWBM	Pressure and Weight-Based Method
PRV	Pressure Reduction Valve
PBM	Pressure-Based Method
QGIS	Quantum Geographic Information System
SCADA	Supervisory Control And Data Acquisition
SI	Supply Interruption
TCV	Throttle Control Valve
UW	Unaccounted for Water

UU	United Utilities
WDS	Water Distribution System
WTW	Water Treatment Work

1 INTRODUCTION

1.1 Motivation and background

Water provision in cities is critical for our everyday lives. However, most of water supply and distribution systems in the western world are now over hundred years old and deteriorating. Under such circumstances, they are unfit to meet the new challenges of climate change, urban growth and changing population demographics in the next hundred years. Radical replacement of the current ubiquitous infrastructure is unrealistic, unreasonable and cost inefficient. The solution is to better manage these systems in a more pro-active, i.e. smarter way. It is therefore no surprise that the worldwide investment in the smart water infrastructure is expected to reach a number billion pounds in the next few years.

More specifically, the water industry in the UK and abroad has a pressing need to better manage interruptions to water supply caused by various failures such as pipe bursts, equipment failures or Water Treatment Work (WTW) shutdowns. One way of doing this is by making use of the increasingly available real-time sensor data collected in Water Distribution Systems (WDS), as well as by using hydraulic models in real-time. However, nowadays real-time sensor data and real-time hydraulic modelling are not used much in a water utility's control room, especially when it comes to identifying a suitable strategy to respond to failure events in near real-time. Relevant academic work has not adequately addressed this challenge mainly due to the focus on specific stages (i.e. isolation, impact assessment or intervention) rather than the overall response process.

Past collaborative work between the University of Exeter and Untitled Utilities has developed an award winning technology that makes use of this data to detect and locate failure events in a timely and reliable manner. What is currently lacking is the methodology for effective response to these events.

Furthermore, for an effective near real-time response there is still a need to develop: 1) improved impact assessment methods that are based on realistic metrics used in the water industry and that are also used in a consistent manner to facilitate easy comparison between different response solutions, 2) more realistic selection of response interventions to be implemented (e.g. based on operational costs, availability of different types of interventions, etc.) and 3) effective interaction with the control room operators that takes into account their expert judgement, preferences and experience.

1.2 Aims and objectives

The Centre for Water Systems at the University of Exeter has a long history of research into water systems modelling and management. This PhD project, which is funded by the EPSRC via the WISE Centre for Doctoral Training, aims to develop, test/validate and demonstrate a new response methodology to support decisions made by control room operators when dealing with various failure events in a WDS. As an integral part of this work, an interactive decision-support tool was developed, entitled the Interactive Response Planning Tool (IRPT). The IRPT is implemented in the programming environment of MATLAB and links to EPANET for the execution of the hydraulic simulations. Also, it links to the Quantum Geographic Information System (QGIS) software to visualise the hydraulic simulation outcome on a map. The IRPT aims to guide/support operators in identifying an effective response solution in near real-time, i.e. usually required up to 1 hour after the event detection/localisation. It is stressed that the target of 1 hour in this thesis is more feasible if unforeseen events in the field, such as non-operable valves, etc., are not considered. The IRPT will be used in this thesis to test and validate the proposed response methodology.

The thesis focuses on answering the following key research questions:

- What is the best way to respond to various events that may occur in a WDS? How can optimal operational interventions be identified and in a timely and automated way? What company data and resources (systems and people) need to be used in the process and how?
- How should the identified response strategy be presented to the control room operator so that he/she can make an effective ultimate decision on how to deal with each event?

- What are the likely benefits and costs of new technology? How will the technology be effectively delivered in to the control room (people, processes and systems)?

The above research questions are addressed via the following thesis objectives:

1. To develop an overall decision support framework for effective near real-time management of events with focus on the response stage;
2. To develop improved methods for impact assessment in the context of real-time response. This includes developing models that are able to (a) better quantify the reduced water consumption in event affected parts of the network;
3. To consider the discoloration potential into the impact assessment process;
4. To develop improved methods for more realistic selection of operational interventions that (a) are driven by actual intervention costs rather than surrogate measures;
5. To develop improved optimisation method in the context of real-time response;
6. To develop methodology that can support effective exploration of operator preferred responses (i.e. manually created responses), in addition to the more automated ones. This involves identification and development of different ‘what-if’ type scenarios and related modelling support.

1.3 Thesis assumptions

In the present thesis some assumptions have been considered for the simplification of the work required. These are the following:

1. The proposed response methodology (implemented via the IRPT) can be applied for certain types of failure, due to simplification of the programming code. Through the IRPT only events, or failures, related to pipe network inadequacy, such as pipe bursts, pipe (planned or unplanned) isolation and WTW shutdowns due to burst can be tested. Additionally, IRPT is able to simulate one single event at each run.

2. The response methodology proposed here identifies response solutions, assuming that the detection and localisation of the failure event have already been conducted. This said, operators implement the response stage after they have successfully detected the event and are also aware of its location. The location of the event (i.e. location of failure pipe in the analysed network) and time of detection are used as input in the programming code for the subsequent identification of the response solution.
3. In the IRPT, changes due to pre-detection phase have not been considered in the impact assessment. The impact assessment of a proposed response strategy starts here from the time that the event was detected in the field.
4. The hydraulic models used here for the validation of the proposed response methodology are not calibrated due to time limitation.

1.4 Thesis structure

This thesis is divided into six chapters including this introduction.

Chapter 2 addresses the first specific objective. In this chapter, a review of relevant literature review is conducted and results presented. Initially, the procedure of Emergency management in different sectors such as the water systems (including the procedure followed by UU), urban security and oil & gas industry is discussed. Subsequently, the Event management procedure, i.e. the management of failures in the water systems, is described. Finally, the gaps in knowledge of response to failures are identified.

Chapter 3 addresses the second specific objective. In this chapter, the response methodology for near real-time response to WDS failure events is described. First, the interactive framework of the response methodology (including the current practice response methodology in UU and other water industries) is presented. Then the impact assessment method used in the response methodology is described. Later the proposed optimisation method used in the response methodology (including a heuristics based optimisation method) is discussed. Finally the implementation of the proposed response methodology through the IRPT developed here is illustrated.

Chapter 4 addresses the third specific objective. In this chapter, the proposed response methodology is demonstrated and validated on a semi-real case study. Initially the semi-real case study is described. Then the proposed response methodology's steps are implemented for the case study's event in order to identify the 'New methodology response'. The 'New methodology response' is ultimately compared to the 'Current practice response' (i.e. response solution based on existing practices of water utilities) in order to demonstrate the benefit resulting from the operator's interaction with the decision-support tool.

Chapter 5 addresses the fourth specific objective. In this chapter, the reliability and robustness of the heuristic-based method for near optimal response to water network failures in near real-time is investigated. The reliability/accuracy of the proposed optimisation method is validated on the C-Town and P-Town case studies. This involves comparison of the heuristic-based solutions with the solutions of a more advanced/accurate optimisation method. A sensitivity analysis is also conducted to validate the robustness of the method.

Chapter 6 addresses the fifth specific objective. In this chapter, the key findings of this thesis are summarised and relevant conclusions are drawn. The novel aspects introduced in this thesis are highlighted, followed by possible directions of future research to enhance and extend the methodologies presented.

2 REVIEW OF LITERATURE

2.1 Introduction

Uninterrupted water supply and high water quality are of vital importance for the human life and key priorities in modern civilisations. WDSs is the water infrastructure that secures the above services and hence, should remain under normal operation conditions, despite the several challenges it may have to cope with due to natural or human causes, such as ageing infrastructure, accidents, earthquakes and power failures.

Although today the WDSs are being monitored in near real-time by contemporary telemetry systems, such as Supervisory Control And Data Acquisition (SCADA) systems, the data generated by these systems is large in quantity and hence cannot be easily managed by the operators. However, the industry has a pressing need to use this data to improve response to the failures in pipe networks (e.g. pipe bursts or equipment failures). Hence, the SCADA systems data should be combined with the real-time use of hydraulic models of the WDSs for an effective emergency planning and response in water utilities (Walski 2015).

This literature review aims at identifying previous work and related gaps in knowledge for the response to the failures. Studies on the detection and localisation of failures are also reviewed for completeness. In addition, the integrated management practices/strategies for response to the failures used by United Utilities (UU) are also reviewed, as these will form the basis for the development of the proposed response methodology.

In the context of this project, the terms *event*, *incident* and *emergency* are distinguished. All these terms refer to failures in the water networks with different impact/severity. To avoid misunderstandings, in the present section of Introduction, the general term *failures* was utilised instead. The above terms are furtherly described in the next sections.

The literature review is organised as follows. Initially, in section 2.2 the procedure of Emergency management is defined. In the context of this section, partial emergency management procedures applied in different, real-life sectors are described. These sectors include the water systems, where the UU emergency management policy is thoroughly described, and other infrastructure systems, such as urban security and oil & gas industry. Subsequently, in section 2.3 the Event management procedure is described. This section reviews academic work related to the management of failures in the water systems, meaning that some of the outcomes are still on a theoretical basis. In section 2.4, the gaps in knowledge of response to failures are identified. Finally, in the last section, all the above are summarised and some conclusions are drawn.

2.2 Emergency management

Emergency is defined as a spectrum of disasters, such as natural disasters, technological disasters or possible attacks (Godschalk & Brower 1985). Emergency management is a sequence of activities (both administrative and informal) undertaken in a coordinated way in order to control emergencies before, during and after they occur (Tveiten et al. 2012). Hence an adequate emergency management procedure includes the following components: mitigation, preparedness, response and recovery (McLoughlin 1985). The mitigation component includes the actions undertaken before the emergency in order to reduce the long-term risk to human life and property (e.g. building codes or disaster insurance). The preparedness component regards the operational development before the emergency in order to respond to it (e.g. emergency operations plans or warning systems). The response component involves the actions immediately before, during and right after the emergency that save lives and minimises property damage (e.g. emergency plan activation, etc.). Finally, the recovery component contains short-term and long-term activities after the emergency to return life back to normal. The emergency management components are shown in the corresponding wheel in Figure 2-1. The strategy for an integrated emergency management is stated in detail at Godschalk & Brower (1985) and McLoughlin (1985).

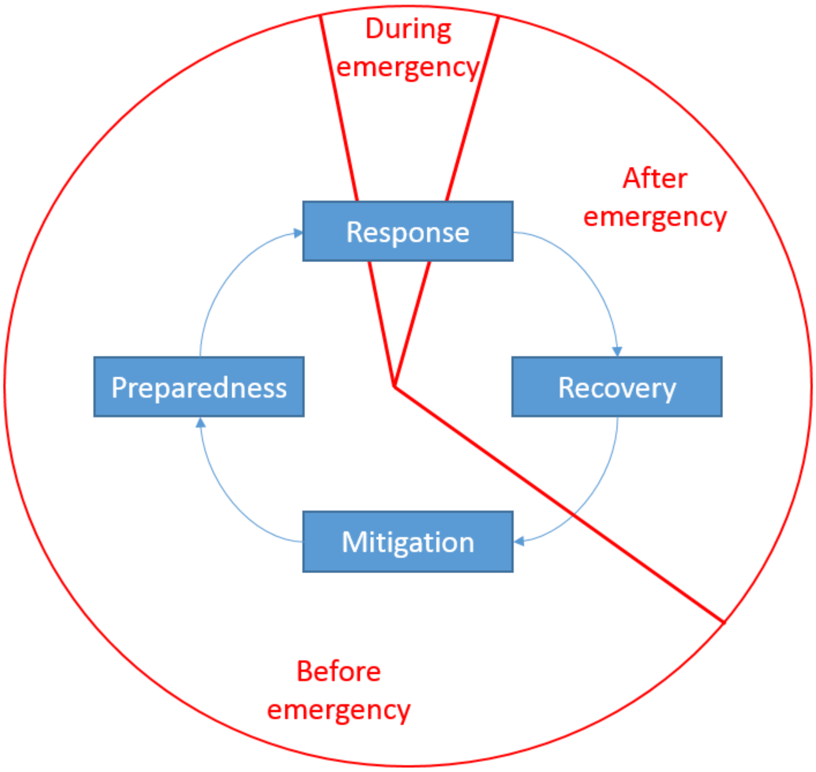

Figure 2-1: Emergency management wheel (Godschalk & Brower 1985, McLoughlin 1985)

The main objective of emergency management is the protection of human life and the mitigation of the impact, economic, environmental or material, especially during natural and man-made disasters (Giordani & Archetti 2017). Natural disasters include extreme weather events (e.g. floods, hurricanes, tornados and tsunamis), earthquakes, volcanic eruptions, landslides, etc., while man-made disasters refer to criminal events, terrorist attacks or accidents (e.g. during the repairing of an element of the urban infrastructure). The impact of these disasters depend on the magnitude of the affected population, the losses of human life, the population's time to recover, the level of infrastructure resilience and other similar factors.

2.2.1 Emergency management in water systems

In the water industry, emergency is denoted as an *event* or *incident*. Events or incidents are any failures that disrupt provision of the regular water service. An *event* is a failure that affects one single property and only a few consumer contacts may follow it. An *incident,* on the opposite hand, is a severe event, whose risk to public health is much greater. Usually, the incident affects groups of properties, causes great public risk and there are plenty of consumer contacts after its occurrence. To this end, throughout section 2.2, these two terms will be used in order to distinguish failures in water systems of different severity.

Early work on the water systems emergency management relates to the preparedness component, and more specifically to the development of warning systems in WDSs. Kumar et al. (1999) suggested a methodology to identify the likely source of accidental contamination in a WDS, as well as to identify the best location/nodes to install monitoring stations. The authors suggested the “t-hr level of service” instead of “q-volume level of service”, for simplification reasons. Based on this suggestion, the time (i.e. t hours) from the contaminant intrusion moment at least one node (i.e. monitoring station) until the detection time is considered in their calculations. Then, by using techniques such as the shortest path and minimum travel time between the nodes in the water network, they managed to effectively identify the contaminant sources.

Nowadays, the management of water systems emergencies, such as pipe bursts or other equipment failures, is carried out by water companies using state-of-the-art hydraulic sensors and SCADA systems. The existing SCADA systems usually make use of control room software that simply displays data received and sometimes offers limited analysis of this data (e.g. trend analysis of pressure/flow signals or similar). What is currently lacking is a more intelligent software that is able to mine the signal data more effectively thus extracting more complex and useful information (e.g. helping answer the question such as is the data received detecting an event in the water system or not, etc.). The latest developments in hydraulic sensors have enabled water utilities to deploy increased numbers of sensors over their networks at moderate cost. In this way, an improved monitoring of the WDS is accomplished and a near real-time detection can be achieved.

The use of the above SCADA system information, as well as a range of other features, have been incorporated in modern, commercial water network software for improved response to water system emergencies. A well-known example of such a commercial software is the Bentley WaterGems (Walski and Parrod 2018). The Bentley WaterGems makes use of an integrated water system model. The integrated water system model not only simulates the current system condition (based on SCADA system information), but it can also simulate different response strategies to a range of emergencies to identify the optimum response.

The Bentley WaterGems can simulate different response alternatives to emergencies, such as shutdowns (planned or unplanned), power outages, fire and contamination events. More specifically, in the case of shutdowns the software provides the capability to identify and properly visualise the isolated segment (i.e. part of network) due to the shutdown. When the isolated segment is identified, users can simulate different measures, such as valve status modifications and others to minimise negative impact to customers. In the case of power outages, the Bentley WaterGems can estimate the time supply will run out after the event and which customers will be affected first. Additionally, in the power outages, the users can simulate different response solutions to identify the optimum one. These solutions include the modification in the operations of pump stations, turning on backup wells, moving in portable generators, or opening interconnections with neighbouring utilities. In fire events, the software provides a range of different measures to simulate in order to identify the optimum response. These measures include turning on additional pumps, opening connections with neighbouring District Metered Areas (DMAs) or pressure zones, closing of Pressure Reduction Valves (PRVs) to lower zones, etc., depending on the severity of the fire event and its location. Finally, in the contamination events the software enables users to visualise the path contaminated water may follow in the water system and assess this spread from various sources. Then it allows users to simulate different measures, such as opening appropriate hydrants for system flushing, to minimise contamination impacts. It is also able to identify the location of these appropriate hydrants based on the initial position of the contamination plume in the model.

2.2.2 Emergency management in United Utilities (UU)

It was earlier stated that in water industry emergencies are denoted as events or incidents. Emergencies in UU are furtherly classified into events, type 1 incidents, type 2 incidents and crisis-type incidents. Hence, emergencies in UU range from more common, minor type events such as pipe bursts and equipment failure to moderate (i.e. type 1) and larger scale (i.e. type 2) incidents (such as e.g. larger scale discoloration events) and ultimately crisis-type incidents caused by virtually uncontrollable natural and man-made disasters.

An incident in UU not only refers to operational incidents (i.e. regarding the disruption of customer service), such as supply interruption or contamination, but also refers to any abnormal situation in the workplace of UU that directly affects the UU system operation and/or the life of employees, such as accidents, power loss or Information and Communications Technology (ICT) system malfunctioning (i.e. security incidents). Operational incidents consist of, for instance, contamination of supply, loss of supply, treatment disruption, network disruption, environmental pollution, fire or explosion, flooding and release of toxic gases.

The incidents in UU are classified into two classes: type 1 and type 2. This classification is based on three factors: magnitude, severity and impact assessed. Type 2 incidents are of a larger scale, more severe and have a greater impact than type 1 incidents. The incident classes, the classification factors and some examples of incidents are shown in Table 2-1. The management of the incidents in UU is as follows (also shown in a flowchart in Figure 2-2): When alarm is raised (or event/incident is reported by the customer), the Duty Manager is the first one activated regardless of whether the alarm is correct or erroneous. The Duty Manager will then formally declare the event or incident, if the alarm is correct. If he/she concludes that an event (and not an incident) has taken place, "business as usual" procedures are followed. If an incident has occurred, then it is first classified based on Table 2-1. The security incidents (i.e. incidents that breach the operational systems of UU or threaten the life of employees) are handled in a separate way requiring the Duty Manager to contact the Police. Afterwards, the Duty Manager will establish a team consisting of the Duty Manager, the Security Manager, the Senior Wholesale Manager, the Public Health Scientist, the Emergency Planning & Response Manager and the Corporate Affairs representative to manage the security incident.

As far as the management of operational incidents is concerned, three key roles are activated, once an alarm is raised: the Duty Manager (who is the first one to be activated, as stated earlier), the Incident Manager and the Forward Incident

Controller (FIC). The Incident Manager and the FIC are roles taken by different UU Managers/Directors depending on the class of incident. The three roles are subsequently described.

During the first step of Incident management, the employees have the responsibility to report the potential incident to the Duty Manager. To report the potential incident they should follow a series of responsibilities, thoroughly described at the relevant UU manuals. It is then Duty Manager’s responsibility to assess for incident potential. If the incident is type 1, the Duty Manager takes the responsibility of its management and the role of Incident Manager. If the accident is type 2, it is the responsibility of Area Business Manager, the Regional Managers, the Level 3 manager and the Director to manage the incident, taking the role of Incident Manager. The above four Managers/Directors are informed to manage the incident by the Duty Manager who calls them for the first incident meeting.

The Incident Manager of each incident type has predefined responsibilities (well-defined in UU manuals), such as securing the health and safety of UU employees (in case of security incidents), establishing an Incident Team and other Task Teams, satisfying customers’ and regulators’ expectations, protecting UU’s assets and reputation, ensuring recovery is planned from the beginning of the incident and carrying out an effective post-incident review including the learning outcomes.

The FIC is the leader of the onsite response activities. For the type 1 incidents, FIC become the Network Team Leader, the Process Controller and the Network or Process managers. For the type 2 incidents, the role of FIC take the Area Business Manager, the Regional Managers, the Level 3 manager and the Network or Process managers. FIC may be the leader of response activities at the location of the incident, however they are still under the guidance of Incident Manager.

Task Teams established by the Incident Manager take over several responsibilities under the guidance of Incident Manager directly after the incident is identified, such as communications across all stakeholders, Affected Area Assessment and visualisation for decision-making, Alternative supplies &

Emergency Plan, Compensation and Legal responsibilities, Emergency Planning Liaison and Laboratory Sampling.

It was earlier mentioned that as soon as the Duty Manager concludes that the alarm corresponds to an incident, an incident meeting is immediately arranged (initial incident meeting). If the incident is type 1, the meeting is virtual, making use of teleconferencing facilities. If type 2 incident takes place, the key participants should physically be present at the meeting (the FIC will dial in). After the end of the incident, the Final/Closure incident meeting is called by the Incident Team, where the incident is officially closed. It should be stressed that the incident is still considered ongoing until the time that Duty Manager issues an Incident Closure Notice.

It was stated earlier that right after the incident identification, among the responsibilities of the Incident Manager is to ensure a recovery plan. This has to be carried out the earliest the possible during the incident. During the recovery plan, the data that have to be collected for the post-incident investigation are collected and sent to the Ofwat, Environment Agency (EA) and Drinking Water Inspectorate (DWI). Additionally, the resources required to restore the UU's reputation are found.

Apart from the above real-time emergency management actions, an integrated Incident management comprises of other “offline” tasks, too. The Alarm Management Centre (AMC) is responsible for the proactive monitoring of telemetry systems in coordination with the Integrated Control Centre (ICC). UU is also a member of Water Industry Mutual Aid Scheme, which enables inter-company borrowing of emergency equipment.

UU makes use of the commercial software Synergi for the hydraulic and water quality modelling of failure events and the simulation of different response strategies. UU is able to simulate via Synergi changes in water quality parameters, such as water age and substance concentration throughout a water network. This functionality is useful when assessing turnover or storage time in service reservoirs or when dealing with water quality complaints or incidents. Water age is a major factor in water quality deterioration within the distribution system. The two main mechanisms for water quality deterioration are interactions between the pipe wall and the water, and reactions within the bulk water itself.

Pipe material and water composition therefore have some influence. As the bulk water travels through the distribution system, it undergoes various chemical, physical and aesthetic transformations, impacting water quality. Depending on the water flow rate, finished water quality, pipe materials and deposited materials (i.e. sand, iron, manganese), these transformations will proceed to a greater or lesser extent. UU have developed proper water quality models in Synergi in order to run water quality analyses and calculate water age. It is also useful to determine the travel time of water through the network for water quality incidents. UU models travel times in Synergi using the water quality analysis tools.

In the case of planned or unplanned shutdowns UU is also able to test different valve closures through Synergi in order to identify the isolated area. Additionally, if rezones and mains rehabilitation are required as response measures, they are able via Synergi to find an alternative supply for an area. In cases where there is no alternative supply, UU is able to model in Synergi an alternative supply vehicle, or ASV, and test if new demand is satisfied.

Table 2-1: UU incident classes and classification factors (UU Operational Incident Management Procedure)

		Type 1 incident	Type 2 incident	Consider for crisis potential if any of below is happening or has a real threat of happening
Magnitude	Scale	Moderate scale & controllable; within one site, within one DMA	Large scale & controllable (geographically at Council or county level)	Large scale and uncontrollable *(e.g. affecting a full Council or county area)* May seriously affect more than one United Utilities directorate *(e.g. widespread IT, telephony or power loss, evacuation of Lingley Mere)*
	Facilities	Affecting a single asset (treatment works, pumping station)	Affecting multiple connected assets or facilities of Regional / strategic importance	Serious damage or threat to facilities of regional / strategic importance, threat to critical national infrastructure, United Utilities or other organisations *(e.g. disruption to regional transport network, critical national infrastructure, major industrial sites)*
	Resources	Moderate support for resource procurement – available United Utilities resources can cope	Widespread support for resource procurement; external / mutual aid required; Partner resources stretched	Major inadequacy in resources *(e.g. widespread industrial action of own staff or key suppliers' employees; widespread fuel supply / transport disruption)*
Severity	Health and safety	No risk to public health	Risk to public health, e.g. BWA H&S issues: (dangerous structures, chemical release, reservoir structural issues)	Fatalities associated with the company Widespread illness among customers Deliberate contamination of water supplies Wastewater incident causing widespread pollution of recreational or environmentally sensitive waters
	Timescale	Will be resolved within 12 hours	Likely to be more than 12 hours to resolve	Will have long running implications and may require major new investment.
	Service, quality and cost	Taste & odour: chlorine › 50 customer contacts or › 1 DMA and 3 calls per DMA in 8 hours Discoloured water: › 50 contacts	No supply › 1,000 props and / or › 1 DMA for › 3 hours	The anticipated cost of response, compensation and recovery exceeds £10 million Widespread service failure and failure to deliver minimum levels of emergency service levels *(e.g. as per SEMD guidelines)* RAID score of 4 or greater for *Regulation, Service and Operations Impact* RAID score of 5 or greater for *Statutory Compliance Impact*
Impact	Customer	Up to moderate impact on GSS, DG or SIM measure Hospital, prison affected and alternative supplies available	Significant impact on GSS, DG or SIM measure; Hospital, prison affected and alternative supplies not readily available Evacuation of › 5 properties	Major impact on SIM Large number of customers affected *(e.g. › 50,000)* Disruption to high profile vulnerable customer groups *(e.g. a major hospital)*
	Regulator (SEMD)	Minimal regulator involvement, notification 'just for information'; BAU reporting; little prospect of regulator sanction or prosecution	Reasonable possibility of successful prosecution or serious sanction	SEMD non compliance in relation to alternative supplies. Prosecution by DWI RAID score of 4 or greater for *Regulation, Service and Operations Impact*
	Civil Contingencies Act	No active multiagency involvement in the response	A multiagency group has been established, including up to strategic level (SCG / Gold), requiring United Utilities to be engaged (including where United Utilities requests such engagement)	Has a multiagency group been established at strategic level to address an incident where United Utilities is a key player and at the root of the incident *(e.g. widespread water loss, widespread flooding, reservoir embankment failure)*
	Media	Local critical coverage from media / political / community leaders	National critical media coverage	Extensive and critical media interest RAID score of 4 or greater for *Political and Media Relations Impact*
	Environment	Localised pollution	Closure or serious curtailment of economic or social amenity	Major fraud Loss of financial market confidence in United Utilities or of sector
	Shareholder	None	None	Major fraud Loss of financial market confidence in United Utilities or of sector

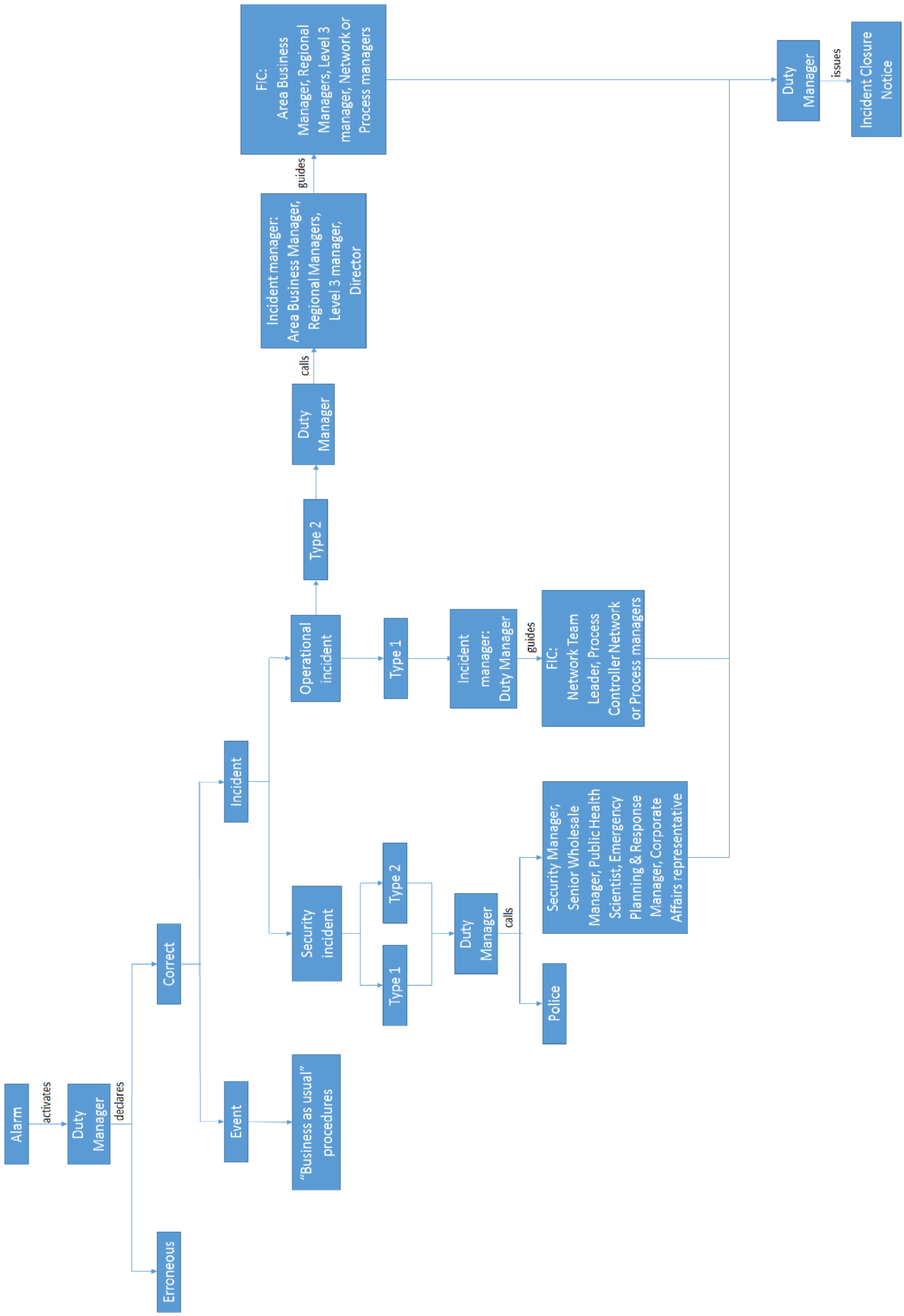

Figure 2-2: Emergency management flowchart applied (before response stage) in UU

2.2.3 Emergency management in other infrastructure systems

Urban security

The pressing need of citizens to feel safe against emergency events, such as terrorist attacks, has motivated defence and security agencies. To this end, multi-sensory technologies are increasingly being developed nowadays in order to more effectively detect, analyse and visualise the emergency events. However, such technologies are associated with a number of challenges, such as manipulation of massive data, widely-dispersed components across the network or heterogeneity of the components.

Recent advances in the multi-sensory technologies not only have addressed the above challenges, but also have enabled related agencies to effectively cope with real-time data (Petris et al. 2014). Another type of technology that has enabled the effective management of the emergency events is the Internet-of-Things (IoT) paradigm. Through IoT methodology the various and different internet-connected components of a system are coordinated. More information about the IoT can be found in Petris et al. (2014).

Giordani & Archetti (2017) in their paper are referred to the emergency management in urban security with particular focus on terrorist attacks as emergency events. They provide a comprehensive review of work related to emergency management in several domains, such as urban security, meteorological events or earthquakes, as well as methods of data analysis in emergency situations when data are collected by sensors deployed over wide areas. They claim that a proactive emergency management on urban security attacks can be accomplished.

Recent advances in methods for early detection of terrorist threats include historical data analysis and statistical learning and allow near real-time prediction of terrorist actions. In the context of this analysis, long-term data (i.e. strategic terroristic behavior) are processed providing a short-term (i.e. operational) activity pattern. The data are generated either by physical devices (e.g. common surveillance cameras) or by virtual sensors (e.g. police officers, citizens). The data are then transformed into symbolic events creating generic scenario-agnostic semantics, or *terrorist indicators*, as found in the related literature.

Finally, the data are processed through reasoning and fusion techniques providing a real-time presentation of the emergency situation.

Data fusion is the technique through which information from different sources are combined to provide robust and complete description of a process of interest (Azimirad & Haddadnia 2015). Data fusion is particularly necessary in cases where massive data need to be collected and suitably processed (i.e. fused and distilled) in order to provide the related users with comprehensible information for decision-making. Joint Directors of Laboratories (JDL) is a well-established data fusion model (Hall & Llinas 2001; Klein 2004), developed by the US Department of Defense to serve military data fusion systems. The model's basic principle is the combination of real-time information flow (from sensing devices to the final user through multi-layers) with an offline layer.

The online multi-layer part consists of four distinct layers (from Level 0 to Level 3), as shown in Figure 2-3. In brief, Level 0 contains the filtering of the raw data. At Level 1 the model entities (i.e. *objects*) and the observations of the objects (i.e. *states of objects*) are defined. Level 2 is in charge of generating *situations* in a micro-scenario. Situations reflect a representation of a set of observations of the object(s) by fusing the states of the objects. The micro-scenario defines the spatial reference system. In the context of Level 3, threat levels are assigned to the situations and presented to the final users. The offline layer (i.e. Level 4) generates, trains and tunes the fusion models and is responsible for the long-term refinement of the model's processes.

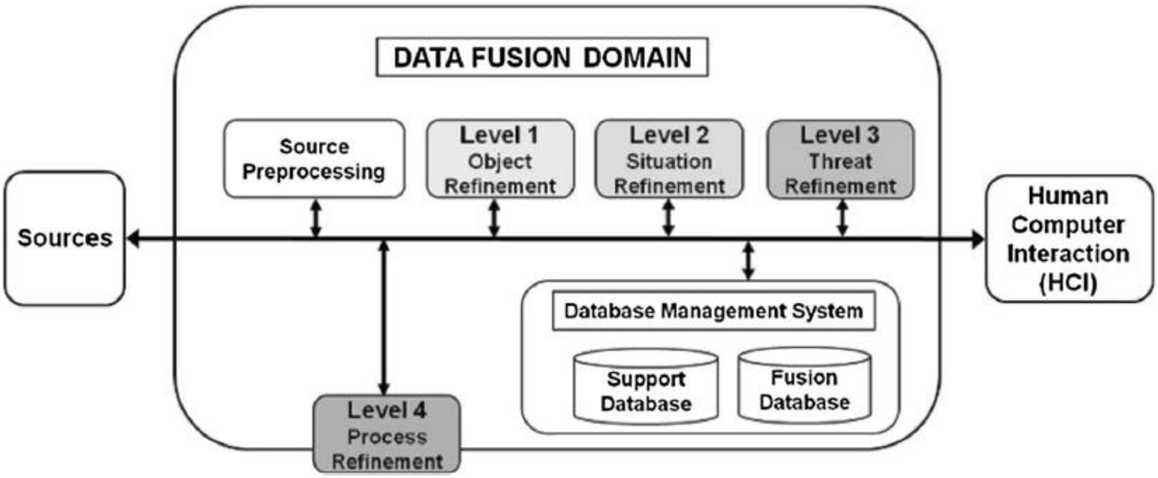

Figure 2-3: JDL layers (Giordani & Archetti 2017)

Oil & Gas

Nowadays, oil and gas industry provides with energy several sectors, such as transportation, electricity, heating, etc. It also offers plenty of job opportunities around the world. Being such a vital infrastructure for the world's economy combined with the fact that the products of oil and gas industry are extremely flammable, make the oil and gas industry attractive to terrorists. Especially after the 9-11 attacks, the need to improve the oil and gas security was intensified.

Successful attacks on oil and gas facilities can cause severe consequences, such as oil/gas supply disruption, economic impact, injuries and fatalities. The emergency management is then of vital importance to secure the human life and uninterrupted processes.

Bajpai et al. (2007) proposed an integrated approach to the management of attacks to oil and gas facilities, including both a preparedness stage and an emergency response stage. The preparedness stage contains a qualitative risk assessment. In the context of risk assessment, a threat analysis, a vulnerability analysis and a security risk factor table are carried out. The threat analysis aims at identifying all possible types of threats and their likelihood to happen. During the vulnerability analysis all the possible scenarios that might cause the threats are recognized. This analysis demands creativity and imagination. Finally, the security risk factor table aggregates the threats and the vulnerabilities of the oil and gas facilities and presents a total security risk status for each facility.

In preparedness stage some security countermeasures are also included. These countermeasures regard cyber security (e.g. protection of crucial information existed in the industry's computational systems or protection of SCADA systems), physical security (e.g. installation of closed-circuit television surveillance at critical places of the industry or exhaustive screening of people and parcels arriving at the industry) and policies and training of employees (i.e. security awareness programmes and acquisition of skills, such as emergency response, bomb threats, first aid, etc.). The emergency response stage comprises of an emergency plan, where several onsite (e.g. medical, safety, etc.) and offsite (e.g. law-enforcement) functional groups are motivated. The steps of the proposed emergency plan are listed in detail at Bajpai et al. (2007).

2.3 Event management

The term *event* is frequently met in the discipline of process engineering and is defined as the cause of an observed abnormality occurring during a process (Venkatasubramanian et al. 2003). Abnormality, or *fault*, reflects any deviation from the normal operation of the process. The activity that addresses the events in order to bring the process back to normal conditions is called Abnormal Event Management (AEM). AEM includes a timely detection of the event, a diagnosis stage where the principle causes of the event are explored and the decisions/actions required to return back to normal operation (Venkatasubramanian et al. 2003).

As far as WDSs are concerned, an *event* refers to any failure that may happen in the network. Events in WDSs can range from minor failures, such as small-scale/single-equipment failures to larger-scale failures, such as large-scale discoloration or pipe bursts. This term has been adopted by the relevant academic literature to denote all the possible types of failure. Hence, e*vent* is a general term used throughout the present section to denote any failure type and should not be confused with the corresponding term used in the water industry (see section 2.2).

An efficient Event management in WDSs can be divided in three stages: Event detection, Event localisation and Event response (Vamvakeridou et al. 2010; Romano et al. 2011; Jung et al. 2015; Kapelan et al. 2017). The first two stages regard the identification of an event in the network and the raising of an alarm. Through identification, the event is quantified in terms of amount of lost water, is subsequently detected and finally located in the network (Romano et al. 2011). The third stage is associated with the decisions and actions required to eliminate the negative consequences (i.e. low pressures, discolouration, etc.) to the consumers (Jeong et al. 2006; Bicik et al. 2009; Nayak & Turnquist 2016) and is the main subject of the present work.

Event response stage includes two sub-stages: Isolation and Recovery. Isolation needs to be carried out with high priority to isolate the failure and allow repairs. Recovery includes the Event impact assessment and selection and implementation of interventions (i.e. Event interventions). Event interventions may not be required, depending on the severity of the failure (Vamvakeridou et al. 2010). The proposed integrated Event management process is depicted in Figure 2-4.

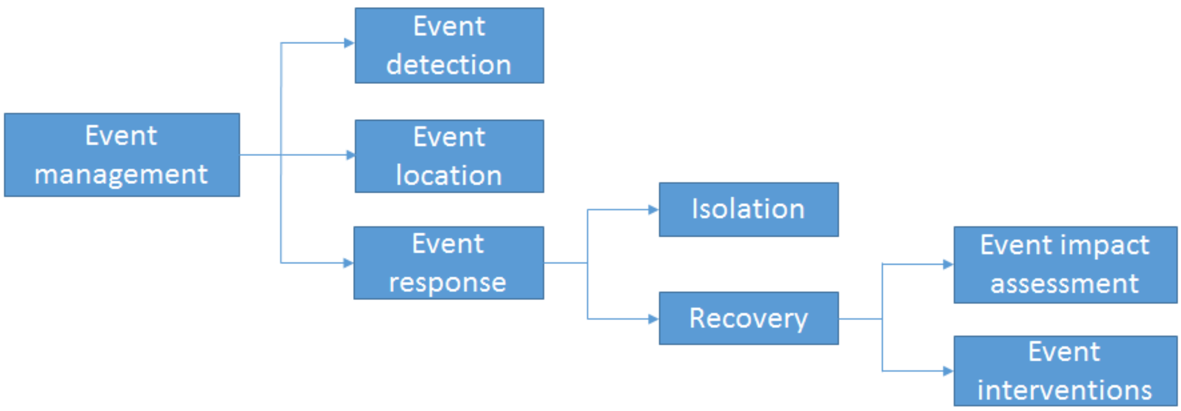

Figure 2-4: Integrated Event management process

2.3.1 Event detection and localisation

As stated earlier, the Event detection is the first stage of the Event management process. Through Event detection, operators are notified that an abnormal situation takes place in the network. Sometimes, it may simply be an erroneous alarm. However, if the alarm is correct, depending on the detection method used, Event detection stage informs the operators of the severity of the event too. For example, when statistical/Artificial Intelligence (AI) data-driven techniques are used, the alarm is raised once a predetermined threshold is exceeded. Operators through these techniques can see how much the threshold is exceeded and hence get an initial view of the severity of the failure. Additionally, if the water company receives many calls for an event, the magnitude of the event may be roughly defined. Although such a critical stage, Event detection is not the focus of the present work. Detailed information about this stage and review of the detection methods developed so far can be found at Puust et al. (2010), Romano et al. 2011 and Laucelli et al. (2016).

There are two types of detection techniques, the hardware-based and the hydraulic-based techniques (Romano et al. 2011). The first ones, make use of specialised devices for the detection of the leak in the network. Although the most accurate techniques in terms of reliability and preciseness, they are only inspecting and not monitoring techniques, hence they cannot be used for the real-time detection of an event in the WDS.

The hydraulic-based techniques make use of the process parameters (i.e. pressure and flow) and are divided into model-based and data-driven techniques. Model-based techniques make use of hydraulic models and can detect the event in the network through the processes of calibration and optimisation (Puust et al. 2010; Laucelli et al. 2016). The drawback of these techniques is that they are time-consuming. On the other hand, data-driven techniques continuously exploit the flow/pressure data collected by the SCADA systems. These techniques allow a real-time event detection and have been more applicable in the real-life challenges of water companies.

While Event detection regards the discovery and a rough quantification of the event in the network, it does not provide any information about its location. Event localisation stage which is the second one is then required for the determination of the event's position. The location of the event can be determined with varying degree of accuracy (Romano et al. 2011). The approximate localisation defines the likely boundaries of the area where the event takes place. Usually, approximate localisation is accomplished when operators using related techniques try to locate the event prior to the field visit. On the other hand, the exact location of the event can be usually determined only after the field visit, i.e. by using specialised equipment (e.g. sounding type devices to locate a leak due to a smaller burst event).

A recent advance in the detection technology has been accomplished by Romano et al. (2010; 2011). The authors developed a contemporary automated detection system, the so-called Event Recognition System (ERS), which can detect the pipe bursts or equipment failures in the WDSs in a timely and reliable manner by using predictive analytics based on statistical/AI techniques. The above methodology was extended by Romano et al. (2011) with the ability to approximately locate the event.

Laucelli et al. (2016) also made progress in the detection stage by introducing the Evolutionary Polynomial Regression (EPR) modelling paradigm. According to the authors, both of the above methodologies enable water companies to react faster to the events, mitigating the negative impacts to the consumers. This also may imply a more effective Event response stage, which is the focus of the present study and is described in the next section.

2.3.2 Event response

Event response is the last stage of the Event management and includes all the decisions and the actions to be made in order to mitigate the negative consequences of a potential WDN event to the consumers. The Event response stage used to be based on a completely manual process. Operators would use their experience to send field workers to check for the alarm. If the alarm was erroneous, that would mean time waste and financial consequences for the utility. Even if the alarm was correct, the response was time-consuming and would result frequently in customer complaints.

Lately, the advances in control systems have partially automated the response to the events. Water utilities identify the significance of the automation of their systems, since the increasingly generated data from the sensors and/or SCADA systems are not manageable by humans. However, their focus is not to completely automate the Event response stage since the human factor is always indispensable when decisions have to be taken. Their target is then to automate as much as possible the process of Event response in order to provide operators with comprehensible information about the event (e.g. location, damaged pipe age, damaged pipe characteristics, time to arrive to the event position, closest valves to the event's location, etc.). This would enable operators to make more informed decisions for a more effective response.

In the literature, such as in Vamvakeridou et al. (2010) and Mahmoud et al. (2018), two Event response stages are distinguished: the stage of Isolation and the stage of Recovery. The first one includes all the actions required to isolate the event in the network by manipulating suitable valves. This stage has been thoroughly studied in the past by several authors, such as Jun and Loganathan (2007) and Giustolisi & Savic (2010), and is not the main subject of the present work. The stage of Recovery contains two more sub-stages: *Event impact assessment* and *Event Interventions.* Event impact assessment regards the estimation of the consequences of the event itself and of the isolation of the event to the rest of the network, as well as the impact assessment of the potential subsequent interventions. Event interventions are the actions to mitigate the consequences and are not always required. The stage of Recovery is the focus of the present work and relevant work will thoroughly be reviewed subsequently. For completeness, some work related to the Isolation is also mentioned.

Isolation

Isolation could be regarded as the first step of the Event response process (Vamvakeridou et al. 2010). The closing of isolation valves generates subsystems in the WDS, which are frequently called *segments* in the literature (Jun & Loganathan 2007; Kao & Li 2007). The isolation of a damaged element not only prevents the failure from expanding to the rest of the system, but also allows easier repair of the damaged element. It becomes obvious then, that being able to identify the segments in WDS is significant. Jun & Loganathan (2007) presented in their paper a comprehensive review of the work carried out in the topic of Isolation and segment identification until then.

Proper distribution of isolation valves takes into account the trading-off between isolating as many as possible elements of the network and the reduction of installation costs. Past guidelines have proposed valves to be placed at both ends of each pipe in a network (Kao & Li 2007). However, budgetary limitations do not allow the development of such networks in real life. Given the budgetary limitations, valves do not exist at both ends of every pipe. Hence, if a pipe failure occurs, existing valves isolate larger sections of the networks (i.e. segments).The manual segment identification is theoretically possible, but in reality (i.e. complex networks) infeasible (Kao & Li 2007). Hence, the development of efficient algorithms for the segment identification is demanded.

The studies about segment identification reviewed in this thesis (i.e. Jun & Loganathan 2007; Kao & Li 2007 and Giustolisi et al. 2008), describe methodologies which are algorithm-based. The above methodologies make use of topological matrices. The topological matrices include topological information of the system elements (pipe network, nodes, valve locations, etc.). The algorithms in Jun & Loganathan (2007) and Kao & Li (2007) search through the columns and the rows of the matrices, which represent the pipes and the nodes of the network, respectively. When at the end of the pipe and/or at a node there is not a valve, the pipe/node is added to the segment. In that way, the isolated segments and the corresponding pipes/nodes within a segment are identified. The algorithm proposed by Giustolisi et al. (2008) use the aforementioned matrices to solve a linear-algebra problem, making some hydraulic-nature assumptions.

Most of the studies associated with the Isolation, also deal with the identification of the unintentional segments in the network (e.g. Jun & Loganathan 2007, Kao & Li 2007). This situation is called in the literature *unintended isolation*. Unintended isolation may result from two potential conditions: Either an element enclosed in a segment may be unintentionally isolated, when no failure has occurred on that. Or a segment that may be connected with the main supply source only through other disconnected segment(s) is automatically isolated (Jun & Loganathan 2007). The first one is caused by the inadequate number of valves in the network, while the second one is related to the lack of network redundancy, or in other words, to the inadequate number of connecting pipes and loops.

There also has been the term *critical segments* for describing the unintentional segments whose isolation causes complete interruption to the downstream network (Kao & Li 2007).The algorithms for the identification of the unintentional segments described in the reviewed papers make use of either of two algorithm-based techniques: The Breadth-First-Search (BFS) or the Depth-First-Search (DFS). BFS is a step-by-step process which searches the network for segment connectivity. It was used by Jun & Loganathan (2007) for the unintended isolation.

However, as Kao & Li (2007) stated, BFS is a time-consuming process and instead they utilised the DFS technique for the identification of critical segments. Hence, the DFS algorithm checks for *articulation points* in a network. Articulation points are the sole connections between two or more subsystems and their deletion divides the system into two or more subsystems, respectively.

Jun & Loganathan (2007) and Kao & Li (2007) also make use of the segment-valve diagram. In the segment-valve diagram, the segments are presented as nodes and the valves as their connecting links. This diagram allows the easier visualisation of the segment expanding after successive valve closings.

Recovery

Recovery is the second stage of the Event response process. It includes the subsequent stages of *Event impact assessment* and the selection and implementation of suitable interventions (called as *Event Interventions* hereunder). Recovery is an iterative process, which starts with the initial impact assessment. The initial impact assessment aims at estimating the impact of the event and its isolation over a pre-specified time horizon assuming no follow-on interventions. This is done by using a suitable impact assessment model ranging from simple quantification of e.g. number of customers affected to more complex and detailed assessments (see e.g. Bicik et al. 2009). If the initial impact is deemed significant enough, a possible operational interventions (including their combinations) are identified and analysed. The optimal interventions are then selected by trading off the related operational costs of interventions and the likely negative impact reduction (estimated by using the impact assessment model mentioned above). The iterative procedure of Recovery is depicted in Figure 2-5 and the two Recovery stages are herein reviewed. They are also presented in Table 2-2 at the end of this section, together with relevant information (e.g. references, methodology types, etc.).

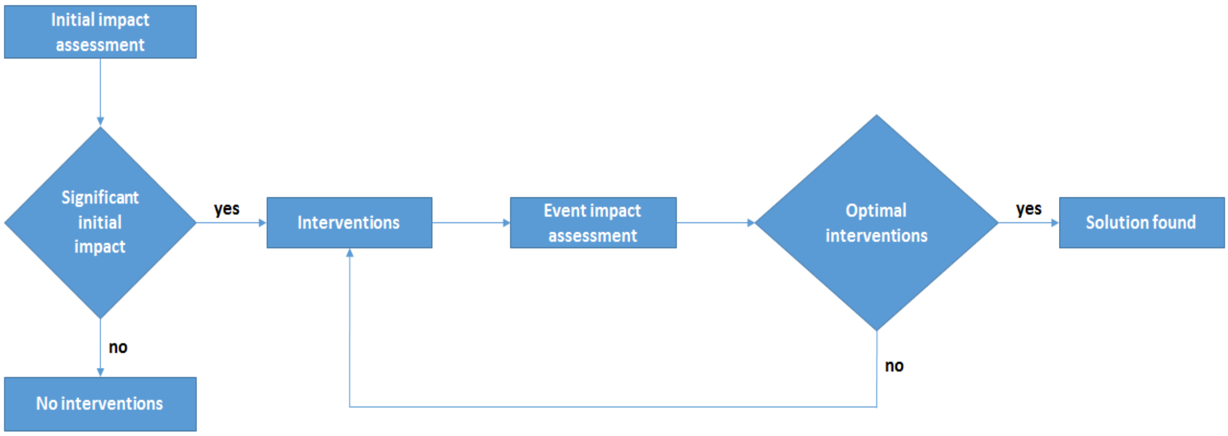

Figure 2-5: Recovery stage of the Event management process

Event impact assessment

Kao & Li (2007) proposed a segment-based optimisation model for decision-making on pipe replacement carrying out a risk-based analysis. For the impact assessment they utilised the pressure-driven model proposed by Gupta & Bhave (1966) and measured the undelivered water volume. For the evaluation of failure rate, they used regression analysis to predict the failure rate of a pipeline per mile per year (described by Walski & Pelliccia 1982) and Poisson distribution to find the general failure potential of the pipeline. The optimisation objective is to maximise the improvement in the water supply reliability in all pipe segments after replacement. The optimisation mathematical model is described in ILOG (2002). The objective (i.e. improvement) is expressed in terms of risk and is equal to the sum of the water shortage of each segment multiplied with the failure rate of each segment. The decision variables is the status (i.e. with failure or not) of each segment. The constraints include the failure rates definition and cost restrictions of the replacement. The authors claim that segment-based models used in replacement/repair decision-making improve water supply reliability. The segment network can be beneficial in other ways too, e.g. in monitoring location siting, partitioning management zones, pipeline network design or expansion.

However this work is not appropriate for near real-time decision making on pipe repair/replacement due to long process of identifying segments, especially in complex real-life networks. Additionally, the authors in their impact assessment considered only one impact aspect, i.e. the undelivered water volume, and no other impact aspects, including discolouration potential, were taken into account.

Giustolisi et al. (2008) developed an algorithm to automatically identify network topological changes due to abnormal system operation (i.e. valve closing to respond to network failure). Their approach is impact assessment coupled with a pressure-driven model to evaluate the water shortage in terms of undelivered water volume due to abnormal operation. Like Kao & Li (2007), they executed Extended Period Simulation (EPS) in EPANET2.0 to calculate the pressure heads under normal and abnormal conditions. Unlike Kao & Li (2007), they adopted the pressure-driven model developed by Todini (2003).

In this model, they carried out some modifications in order to improve the convergence of the solution. They still, though, used the equation of Wagnar et al. (1988), for the calculation of water-shortage volume, based on the aforementioned calculated pressure heads. According to the authors, the proposed algorithm is novel in identifying topological network changes, which can be useful for managing planned and unplanned interruptions to the water supply. However, the case-study did not present potential of the new method to be applied in near real-time decision-making on response to water network failures.

Kapelan et al. (2006) carried out a risk-based analysis, estimating both the impact of a failure in the network and the failure probability rate. The authors made use of pressure-driven analysis (proposed by Giustolisi et al. 2008) in an extended period simulation for the impact estimation. The impact was measured in undelivered water demand to the customers. For the calculation of the failure probability rate, they utilised the relationship of Bernardi et al. (2005), which is dependent on the pipe characteristics. The method was tested on the simple real-life network of Apulian town in southern Italy. The method could potentially be used to support near-real time decision-making about repair planning, as well as to evaluate the expected reduction in risk due to pressure management or rehabilitation. However, the method considers only undelivered water demand in the impact assessment (i.e. different impact aspects including discolouration potential are not considered). Additionally, the method is not tested on more complex real-life networks.

Beuken et al. (2008) developed a water quality index in the context of a quantitative risk analysis. They suggest to calculate discolouration risk based on minimum and maximum velocities and maximum flow rates. The minimum and maximum flow velocities in an average demand day are calculated with a hydraulic model for each pipe. The same model is used to estimate the largest flow rate for each pipe under the same demand conditions. Then, a score is assigned to each pipe for each discolouration risk type (i.e. based on velocities and on flow rates). A score of 1 means low, a score of 2 means moderate and a score of 3 means high discolouration risk.

The discolouration risk for every pipe is calculated as the sum of the scores based on both velocity and flow rate. The resulting discolouration risk scores are grouped in five severity categories, i.e. “VERY LOW” with a total score of 2, “LOW” with a total score of 3, “MODERATE” with a total score of 4, “HIGH” with a total score of 5 and “VERY HIGH” with a total score of 6.

Once the discolouration risk score for every pipe has been found, the discolouration risk increase for every pipe can be calculated as the difference between the discolouration risk score under ‘failure’ and normal conditions. The ‘failure’ condition is defined here as the WDS condition after the occurrence of the event and/or the implementation of the intervention(s). Similarly to the normal condition, the DRI under failure condition is calculated in a pressure-driven EPS hydraulic model which simulates the failure network. The discolouration risk increase is then ranked based on the total score increase, i.e. “NO RISK” with a total score increase equal to 0, “LOW INCREASE” with a total score increase equal to 1, “MODERATE INCREASE” with a total score increase equal to 2 or 3 and “HIGH INCREASE” with a total score increase equal to 4.

In the context of this thesis, the above paper in combination with the work of Bicik et al. (2009) (see subsequently) were used for the estimation of the discolouration risk increase index. In this thesis, it was regarded that calculating the number of pipes that are in danger of discolouration risk increase is a more comprehensible way of presenting to operators the water quality condition in the network. Operators in water utility practice do not necessarily concern about the number or direction of the particles in the water pipe during the event. On the contrast, they concern about which pipes in the network show risk of discolouration increase in order to inform customers in the affected areas and avoid customer complaints.

Bicik et al. (2009) proposed an impact model which evaluates the negative effect of WDS failures from an operational rather than strategic point of view. The proposed impact assessment has been partially adopted in the current thesis and hence described here thoroughly. The operational perspective is short-term (e.g. short-term failures caused by pipe bursts) and allows better prioritisation of decisions in the operating room. Hence, the model can assess the impact of a failure to the customers based on a list of Performance Indicators (PIs). They make use of existed PIs developed by the pertinent authority in the UK, Ofwat. Existed PIs measure the long-term pressure adequacy (i.e. DG2) or the long-term water supply continuity (i.e. DG3). However, the authors believe that these PIs are insufficient in estimating the impact, since they reflect a long-term (i.e. strategic) perspective, and they do not take into account the type of customers and their vulnerability to the failure. According to the model, the effects of the different impact factors are listed in a table based on the value tree proposed by Michaud & Apostolakis (2006). According to the table, there is mainly social impact to the customers and economic impact to utilities. The proposed impact model includes PIs for the following impact factors: low pressure, water supply interruption and discolouration. The quantities that measure the first two PIs are calculated in the hydraulic solver EPANET2.0 (a modified version which takes into account pressure-driven analysis). For the estimation of discoloration potential, the hydraulic model is coupled with an offline model which relates the calculated disturbances in the normal flow to discoloration potential.

The low pressure PI for the impact to customers measures three quantities as surrogate for the social impact: the number of customers affected by low pressure, the volume of undelivered water due to low pressure and the average low pressure duration. It should be stressed that each of the three above quantities are calculated for four different types of customers. The low pressure PI for the impact to utilities estimates the economic impact measuring the lost revenue due to low pressure, taking into account the amount of metered and unmetered customers.

The water supply interruption PI measures the same quantities as in the low pressure PI and the duration of the interruption lasts from its beginning until it is fully recovered. Furthermore, five different duration classes are proposed to distinguish the severity of the interruption. Finally, each quantity of the PI is calculated for every customer type. The discolouration PI measures the number of pipes that are more likely to experience the phenomenon. The estimation of the discolouration likelihood was carried out by the model proposed by Dewis & Randall-Smith (2005) and is based on risk trees. However, the authors believe that a discolouration model based on shear stress would be more appropriate. They finally made use of Geographical Information Systems (GIS) for the visualisation of the results (i.e. properties with low pressure and/or interruption, height of pressure at nodes and increased discolouration potential for each pipe). The method was applied on a large real-life WDS. The method provides insight regarding the proper evaluation of negative impact of WDS failures, but there is no evidence in the paper that it can be used in near real-time decision making.

Diao et al. (2016) developed a Global Resilience Analysis (GRA) methodology in order to evaluate and enhance resilience in water infrastructure under extreme conditions. GRA is a risk-based analysis of the system differentiating from other related studies due to the focus on the failure modes that stress the system rather than the threats. They distinguish the failure modes from the threats by saying that the failure modes typically are pipe failure, excess demand, and substance intrusion, which are caused by internal (e.g. water hammer) or external threats (e.g. ground movement). The method has been applied in four different WDSs for the aforementioned different failure modes. Impact is measured through the ratio of unsupplied demand to the total demand. The results show that the GRA can identify the range of impact under different scenarios for each failure mode. It is also shown that increased resilience in one failure mode may lead to decrease of resilience to another one. The authors in this study developed a computer program in C# which calls Epanet engine for hydraulic and water quality simulations. However, they simplified their numerical calculations by omitting some scenarios due to ill-conditioned equation systems. Their approach also might be more appropriate for strategic system assessment/enhancement rather than real-time impact assessment, because the main aim of the method is to assess/enhance system resilience in the long term.

Qi et al. (2018) developed an impact assessment framework which includes both hydraulic and water quality impact indicators. In the context of the proposed framework, statistical analysis of the different impacts also takes place, the spatial distribution of each indicator is analysed and finally the pipes of the network are ranked based on each individual impact indicator as well as single indicator (i.e. considering all aspects of impact). The framework was tested on three different WDSs and the results indicate that impacts of pipe breaks are depended on pipe diameters, pipe locations, time of break and the indicator considered. The above analyses are conducted with the aim to provide guidance for effective event management and restoration planning strategies in a water utility. However, the proposed impact evaluation framework might be more appropriate for strategic (i.e. long term) rather than real-time response planning to a network event (e.g. break, etc.). This is due to the fact that its focus is to provide a good understanding of network properties after analysing different break scenarios which run offline.

Event Interventions

Selection and implementation of interventions is the last stage of the Recovery phase. At this stage, the decisions are made and the actions are taken to minimise the previously estimated negative consequences of the failure event. This is the most crucial part of the Event management process. However, the decisions made during this stage are strongly dependent on the previous steps of the Event management process. Hence, an effective Event management plan should develop methodologies taking into account all the aforementioned stages (i.e. *Integrated Event Response* methodologies). Such methodologies are usually parts of Decision Support Tools (DST) in water utilities. Some of such methodologies are described in this section. For completeness, the separate stage of Event interventions is described in this stage, though.

Jeong et al. (2006) developed a mathematical mitigation model for the minimisation of the consequences of a physical attack that leads to water supply disruption in a part of the network. The interventions here are the successive demand adjustments across the residual network until the desired pressure heads are satisfied and impact minimisation has been achieved. Model input are the residual network, a demand level and a priority level of each node. Hydraulic simulator EPANET2.0 is used for the control of the hydraulic feasibility (i.e. control of mass and energy conservation and pressure adequacy of the residual network after the demand-level changes). Although in real life water demand at a customer node cannot directly be controlled, in emergency situations voluntary participation of customers is anticipated. Observations have shown that a reduction of at most 50% can be achieved when customers are informed properly and are available to help (Jeong et al. 2006). Hence, in the context of the model, three demand levels are defined: 0 (water supply discontinued, no demand satisfied); 1/2 (half demand satisfied); and 1 (all demand satisfied).

Once the demand has been determined, the flow and pressure characteristics of the residual network are calculated using the hydraulic solver EPANET2.0 to check for hydraulic feasibility. The consequences of water shortage on a node are measured through the objective function which considers two factors: the priority level (i.e. importance) of that node and the negative impact of reducing the normal demand to a specific level on the node. The negative impact is calculated using predefined theoretical impact functions/curves which take into account the customer sensitivity. The model aims at mitigating the above consequences (i.e. minimising the objective function) by creating a feasible demand pattern in the residual network. The impact function takes the three demand options and returns impact severity for each node (i.e. implicit impact estimation).

Five methods are proposed for the solution of this optimisation problem. The first two search for optimal solution: The Branch-and-Bound (B&B) algorithm and the Genetic Algorithm (GA). The three others are heuristic methods: The Pressure-Based Method (PBM), the Weight-Based Method (WBM), and the Pressure and Weight-Based Method (PWBM). According to B&B, the solution space is represented by a search-tree. Every level of the search-tree corresponds to a customer and every node at each level corresponds to a demand option (among the three aforementioned options). The method starts searching for a solution from a node called root. After checking for hydraulic feasibility (through the constraint functions) in the solver EPANET2.0, a potential solution is generated across the search-tree, which is reflected in a path. Each solution represents a demand pattern. To accelerate the method, the techniques of search strategy and pruning are used. More details about the B&B method can be found in Beale (1979). B&B method, although simple and easy to program, can be time and space consuming, particularly for large networks (Jeong et al. 2006). In such cases, Jeong et al. (2006) proposed the GA methodology to search for the optimal solution. Here the solution space consists of the candidate solutions, namely individuals. GA iteratively looks for the optimal individuals by modifying the solution space.

In the work of Jeong et al. (2006), each individual includes a set of genes and each gene represents a demand option. Like in the case of B&B, each solution is checked for hydraulic feasibility against the constraint functions. The techniques of point crossover and random mutation are used for the generation of new offspring. The three last heuristics (PBM, WBM and PWBM) aim at finding a feasible demand pattern based on the idea of reducing one level of demand at the top-ranked node. The ranking of nodes differs for each heuristic method. Hence, the residual network is submitted to the solver EPANET2.0 and if inadequate pressure distribution is returned, the demand level is reduced by one in the following way: In the PBM method the top-ranked node selected for demand reduction is the node with the smallest pressure (but still positive demand). In the WBM, the selected node is the one with the lowest priority level. Finally, in the PWBM, the selection of the top-ranked node takes into account both the pressure and the priority level of the node.

The general methodology was applied to three networks: two small ones (12 and 24 customer nodes) and one large network (685 customer nodes). The results showed that the B&B method is regarded more efficient than the heuristics in the small networks. However, as far as the large networks are concerned, the GA is more efficient than the other methods in providing the optimal solution (Jeong et al. 2006, Jeong & Abraham 2009). Furthermore, the authors observed that if the solutions from the heuristics are incorporated in the initial population of GA, the algorithm may be more efficient.

One of the eliminations of this research is that the methodology was applied in artificial networks and each network was located in a single pressurized zone. Real-life networks, though, include multiple pressure zones and several assets for adjusting the flow, such as pumping stations, water tanks, etc. Moreover, the applied methodology assumed a static demand pattern without taking into account the demand peaks in a 24-hour horizon. According to the authors, if the daily peaks were taken into account, the consequences of the water shortage would further be reduced. Furthermore, the impact assessment of the demand reduction is carried out through theoretical impact functions/curves. On the other hand, the advantage of the proposed methodology is that takes into account the customer sensitivity to the water shortage and the customer behaviour under failure conditions (i.e. reduction of normal demand).

Jeong & Abraham (2009) expanded the approach proposed by Jeong et al. (2006) in a more realistic way taking into account the dynamic demand pattern during the day. Their approach was also more reasonable, because they proposed water rationing plans for different types of customers. According to these plans, water is supplied to the affected customers at least for a short-period during the day (instead of complete water supply shut-off in some customer nodes during the restoration, as Jeong et al. (2006) had assumed).

Three different types of customers are assumed in this study: residential, industrial and critical customers. The consequences of the partial water supply are measured in a different way for every customer type. All three consequence measurements make use of the degree of impact of the selected water rationing plan. For the estimation of the degree of impact, the impact curves mentioned in Jeong et al. (2006) are used, as shown in Figure 2-6. Each impact curve/function corresponds to a different customer type. Hence, the curve f1 describes the consequences of a partial supply to highly sensitive customers. Curve f2 represents a linear impact. Finally, curve f3 reflects customers with the lowest impact of a potential partial water supply. For the residential customers the impact function f3 is assumed. In the case of industrial customers all three impact curves are used, because three different types of industry are assumed. For the critical customers, the impact curve f1 used.

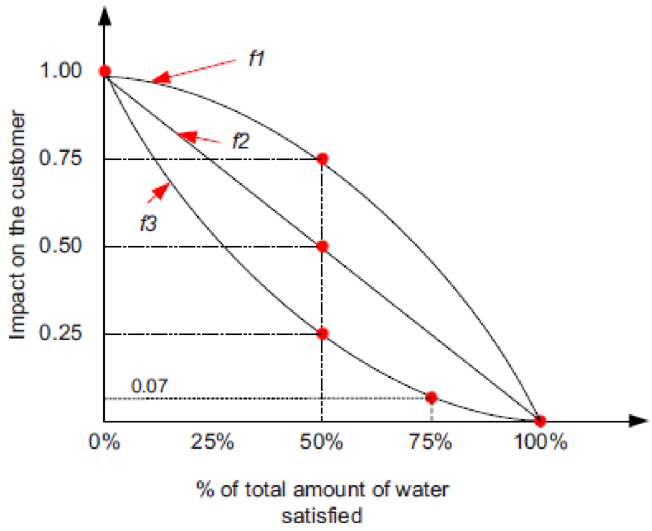

Figure 2-6: Impact function curves for the impact estimation of a potential partial water supply to different types of customers (Jeong & Abraham 2009)

The consumption pattern is also determined for every customer type. As far as the water rationing plan for residential customers is concerned, the typical graph of diurnal consumption (i.e. one peak early in the morning and one peak early in the evening) is utilised. A simplification of this graph, though, is eventually assumed. According to this simplification, step-wise periods of time, during which the consumption remains constant, are used. The time steps, or *segments*, have four hours duration. To fully or partially cover the water needs of the customers only ten different (and most representative) water plans are suggested: One plan for full water supply during the day and two plans for partial supply (three plans of 8-hour supply and six plans of 4-hour supply).

As far as the industrial customers are concerned, the consumption pattern was classified into three categories: the typical one where water consumption takes place during the working hours (from 8am. to 5pm.), the typical restaurant consumption from 5pm. to 9pm. and the night consumption by facilities with water tank for energy-saving reasons. For each type of industry customers, four different water rationing plans are proposed by the authors: one full supply, two partial supplies and no supply. Finally, the first and third aforementioned consumption patterns were used for the critical customers, as their consumption broadly varies depending on their service. The corresponding water supply plans were also used.

The above consequence measurements form the three objectives (i.e. objective functions) that need to be minimised. For the solution of this multi-objective optimisation problem, the Non-dominated Sorting Genetic Algorithm, type II, (NSGA II) is used. For the control of hydraulic feasibility of the proposed water supply plans, the authors made use of EPA in the hydraulic solver EPANET2.0. The optimisation process is shown in Figure 2-7.

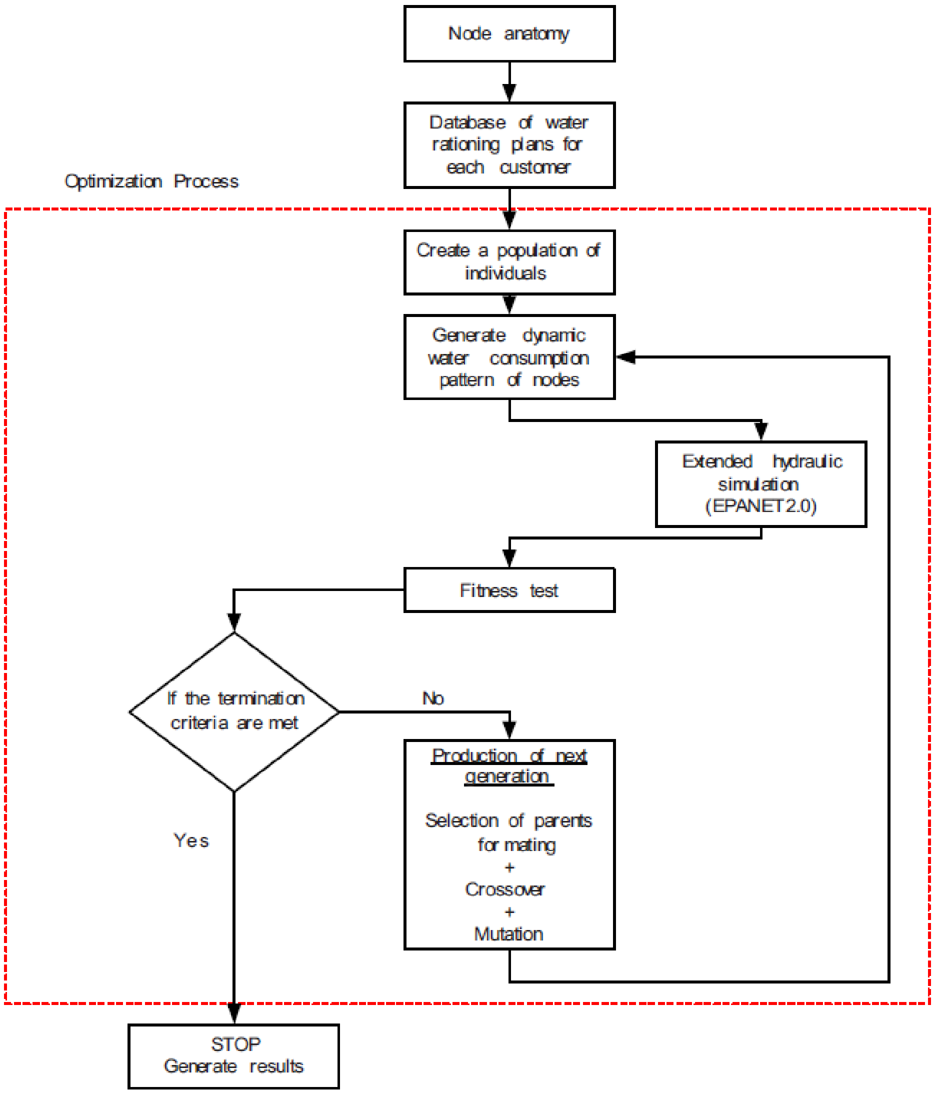

Figure 2-7: Optimisation process to find the optimal water supply plan to the different types of customers in the work of Jeong & Abraham (2009)

In addition to the water rationing plans, the authors examined the role of water tanks immediately after the disaster. They found out that increasing the tanks capacity or maintaining a high level in the tanks can significantly reduce the negative consequences. Hence, increased tank capacity will provide with water the destroyed part of the network for the first days immediately after the disaster, eliminating the consequences and enabling emergency managers arrange their mitigation strategies. However, water companies should consider additional costs for acquiring increased capacity tanks, as well as issues related to water quality.

The advantage of the model is that it can be applied at water shortage situations not only due to physical attacks (as the study assumes) but also due to extreme natural events. To this end, the proposed methodology could be applied under other extreme water network events, such as large-scale pump or pipe failures/bursts. One of the limitations of the model is that the demand is not dependent on the pressure. Hence, potential pressure reduction due to leakage or unaccounted for water that implies demand shortage is not taken into account in this model. Another limitation of the study is that the demand scheduling for the water supply plans takes place based on the volunteering participation of the customers. Such an assumption, though, is very unsteady and the authors believe a valve-controlled method should be developed for this reason.

Turner et al. (2012) also developed a mitigation methodology when physical attacks or extreme natural disasters strike the water infrastructure. The same assumption as in Jeong et al. (2006) and Jeong & Abraham (2009) was made: After the disaster, the system is divided into the damaged and undamaged (or residual) one. The damaged sub-system is isolated to allow for repairs, while the residual system must be hydraulically supported in order to meet the minimum pressure requirements at all demand nodes. In the study of Turner et al. (2012) reconfiguration of the residual network is also carried out through demand adjustments.

Unlike Jeong et al. (2006) and Jeong & Abraham (2009), they propose a valve-based isolation technique to change the demand levels at the nodes of the residual network. Their suggestion of interventions is to pressurise a set of demand nodes in the residual network that are accessible and deliver water through trucks from these nodes to the nodes in the same residual network that are not accessible (and hence unpressurised). The objective of their study, which is reflected into the objective function, is to minimise the sum of the costs of not providing the required demand to prioritised sub-systems and of transportation from pressurised to unpressurised sub-systems in the residual network. The model of the selected network is skeletonised (i.e. a single demand node represents several customers of the same neighbourhood). It is also divided into *sectors*, which include several customer demand nodes. Each sector is assigned a priority weight to account for customer sensitivity. Based on that weight the corresponding cost index is calculated reflecting the cost of not pressurising the specific sector. The above costs are normalised dimensionless quantities, providing an implicit way of measuring the consequences of the water shortage. The problem is solved using linear optimisation, by converting the non-linear constraints into linear through some assumptions/relaxations.

The authors believe that their study contributes to controlling the computational time through the relaxation/linearisation methods they proposed. Other advantages include that they consider the customer sensitivity through the weight factors for ever sector they assume and the real-life network applications of their model. Some limitations of their study are the assumption static demand patterns and that the cost indices they proposed have been calculated based on high level of abstraction.

Integrated Event response methodologies

The current advance in SCADA and data logging technologies has enabled water utilities towards more real-time reactions to WDS events (Bicik et al. 2008). However, the massive data generated by these systems cannot be effectively processed in the operating room, despite the technological development of control systems. Hence, so far the WDS operation under failure conditions has mainly been approached from a strategic point of view, which focuses on the long-term water supply management (Bicik et al. 2008, Bicik et al. 2009). As a result, operators need support for a near real-time response to a failure. The focus should then be concentrated on how to provide them with comprehensible information and let them make the decisions, rather than substitute them.

Water industry has also realised that a more realistic representation of failure implies a risk-based approach rather than a sole looking at either the impact or the frequency of the failures in the WDS (Bicik et al. 2008). Such approaches can later on be part of Decision Support Systems (DSS) in order to enable the decision-making. Subsequently, some integrated methodologies that consider the above are proposed. These methodologies basically implement the three aforementioned steps of the Event response process (i.e. Isolation, Event impact assessment and Event interventions) and are also presented in Table 2-2.

Bicik et al. (2008) proposed a risk-based DSS methodology for supporting operators in decision-making against a failure. The methodology is based on the general process of WDS under abnormal conditions. Figure 2-8 presents the steps of a WDS operation once an abnormal event has been captured. The Data Collection is carried out automatically by the online sensors placed in the network in form of time-series. At this stage, the notifications by customers in form of phone-calls are also included and processed manually by the operators. The Filtering process takes place automatically in order to reach a level of confidence that the abnormal event is real. Once some confidence has been gained, an Alarm is generated automatically. The Investigation step then follows, which includes the actions to be made in order to assess if the perceived problem is real. At this stage, there is the automatic process of the risk estimation of each potential incident associated with a specific alarm and the manual process of field inspection, if needed.

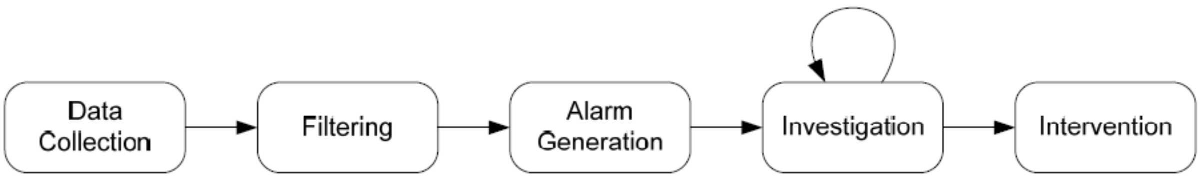

Figure 2-8: Steps of WDS operation under abnormal conditions (Bicik et al. 2008)

The structure of a DSS which works on a risk-assessment basis is depicted in Figure 2-9. The Detector module includes the three first steps of the WDS operation under abnormal conditions (as depicted in Figure 2-8). The Detector also identifies a set of potential incidents for each alarm generated. The Risk Evaluator module in fact represents the Investigation step of Figure 2-8. This module turns a WDS operation under abnormal conditions into risk-based. At this stage, the risk is estimated for each potential incident (of a specific alarm) in order to prioritise the intervention actions. The partial risk of each incident is presented in a non-aggregated form (i.e. the probability of occurrence and the impact to customers are presented separately). Hence, once an alarm has been prioritised, the operator is able to identify the real cause (i.e. incident) of this alarm, which may not have the largest risk (but either the largest impact or the largest probability). The partial risks are subsequently aggregated to form an overall risk of the specific alarm in order to prioritise the alarms generated. The alarm prioritisation is accessed by operators using an aggregation function based on Yager's Ordered Weighted Averaging (OWA), which reflects the operator's level of risk-aversion. The Intervention Manager includes an offline database with interventions to a particular incident, which is automatically retrieved when a specific alarm is raised. It also includes the decision-making of the operators, who select an intervention from the database or even combine/modify interventions aiming to the risk reduction. The interventions provided by the database are in this case only valve manipulations, depending on the incident.

The Risk Evaluator module, specifically, includes the impact evaluator and the probability evaluator. The probability is calculated using the Dempster-Shafer theory of evidence. According to the theory, several independent bodies of evidence are utilised and the corresponding levels of belief and plausibility (i.e. probabilities) are estimated. Each body of evidence can dynamically change, based on the quality of its success. Additionally, most of the bodies are time-dependent, allowing the corresponding probabilities to change, if new evidence is available. The impact is calculated using an impact model based on a list of basic impact factors. The impact factors are classified based on the interested parties forming a value tree (Michaud & Apostolakis 2006). The different impact factors are calculated using pressure-driven analysis in EPANET2.0. The results are then integrated with GIS to visualise them to the operators.

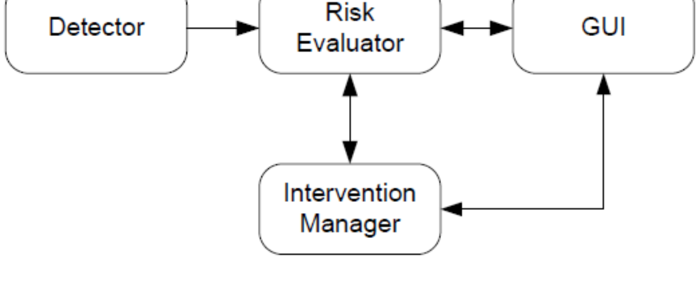

Figure 2-9: Structure of a risk-based DSS (Bicik et al. 2008)

Vamvakeridou et al. (2010) proposed an integrated Intervention Management Model (IMM), in the context of a general DSS methodology for operational WDS management. The IMM takes into account the two successive steps of the Event response stage (i.e. Isolation and Recovery). These two separate steps are implemented in two different modules, the IMM1 and IMM2, respectively.

As far as the IMM1 is concerned, the methodology by Jun and Loganathan (2007) for automatic Isolation was followed, even though the event has not been verified. This stage is carried out taking into account the minimum impact on customers, which implies optimal closing of valves. The IMM1 is split into two parts: the offline and the online part. In the offline part, all possible sets of valves to isolate the network segments have been recorded on a database. These sets correspond to different failure scenarios and for each one of them the optimal valve closings are proposed. The online part, which in fact is the IMM1, runs through the database in real-time after an alarm has raised and provides the operators with the optimal valve closings.

After the identification of the failure, IMM2 takes place. IMM2 consists of the Event impact assessment and the Event interventions. Event impact assessment is conducted using hierarchical aggregation of partial impact indicators. The partial impact indicators are found in Bicik et al. (2009), where the discoloration impact factor is estimated using the model proposed by Dewis & Randall-Smith (2005). It is worth stressing the innovative partial factor “system impact”, which among others (water lost and metered undelivered demand) counts for the 3rd party damage too. The calculation of the partial impact factor is conducted in an extended form of EPANET2.0 which takes into account the pressure-driven analysis, applying EPS. The final impact factor results from the hierarchical aggregation of the partial ones and is presented to the operators.

After the initial impact assessment of the failure, the manual activation of operators takes place, where they have to find the optimal solution to alleviate the estimated failure impact. Three intervention options are included in the IMM2: valve manipulations in the same DMA or between DMAs, the change of PRV status and the installation of overland bypasses. Due to the unlimited number of sets of interventions needed to reduce the impact, Multi-Objective Genetic Algorithm (MOGA) takes place. The two objectives are the minimisation of impact and the minimisation of the interventions. The decision variables considered are the three aforementioned intervention options. The optimisation is coupled with a heuristic algorithm partially based on the Discrete Dynamic Dimensioned Search principles, in order to reduce the initial number of MOGA candidates.

The above impact assessment process is also carried out for the estimation of the impact of the proposed intervention(s). After the impact assessment of each or combination(s) of interventions, the Analytic Hierarchy Process (AHP) is applied. AHP is a qualitative process, where the decision maker pairwise compares two different criteria or indicators. The qualitative character of the process is reflected in the linguistic definitions listed in a matrix, which operators can use to rank the potential interventions.

Mahmoud et al. (2018) also proposed an integrated methodology for near real-time response to pipe burst events in WDSs. The proposed methodology includes all the stages of Event response: Isolation and Recovery (Event impact assessment and Event interventions). However, the Event interventions stage is the one where they suggested a new methodology, as the rest of the stages were based on existed methodologies.

The first stage of the response methodology (i.e. Isolation) is addressed by a combination of methodologies developed in past studies. As defined by Jun & Loganathan (2007) and mentioned earlier here, the disconnected area around the event is called *segment*. Both the segments and the unintended segments are identified into the network utilising the methodology developed by Giustolisi & Savic (2010). Finally, the algorithm of Jun & Loganathan (2007) is used to identify the closest set of valves.

For the impact estimation, an impact function, called performance indicator (IM), is proposed. IM is expressed in terms of undelivered water volume to consumers. The initial impact assessment regards the impact of the isolation (i.e. first Event response stage) of the event. However, the same impact function is subsequently used for the impact estimation of the application of the proposed interventions (described later). The undelivered water volume results after subtracting the delivered demand at a specific node from the required demand at the same node, when the actual pressure is less than the required pressure. The required demand is generated by historical operational data. The delivered demand is calculated by an implicit pressure-driven analysis in the hydraulic solver EPANET2.0. The Recovery stage includes a recovery optimisation problem. In the context of that, a two-objective optimisation problem is solved. The first objective is the minimisation of the impact, which implies the minimisation of the objective function IM. The second objective is the minimisation of the operational cost, which is associated with the minimisation of the number of intervention options, expressed in the objective function INV. Three distinct options are considered, as in Vamvakeridou et al. (2010): valve manipulations, PRVs' outlet pressure adjustments and installation of overland bypasses from nearby hydrants.

In order to minimise the computational time and make the response more real-time, an offline assessing procedure takes place. According to it, the single interventions, valve manipulations and overland bypasses, are checked for feasibility (i.e. if their impact is less than the impact of the initial isolation). The single intervention PRVs' adjustments is not checked for feasibility, as it is in advance assumed as a non-feasible single intervention, in cases of full water supply interruption (Vamvakeridou et al. 2010). For the assessing procedure, a reference value of impact (IMR) is estimated and compared with the impact of a selected single intervention. The IMR regards the option "do nothing" and, in fact, reflects the estimated impact of the first-stage Isolation. The process is iterative until all the possible single interventions are checked for feasibility. The successful candidates proceed to the optimisation stage. The assessing procedure is shown in Figure 2-10. After this offline process, an online (i.e. after the detection/localisation of the event) procedure takes place. During this procedure, based on hydraulic simulations the flow directions are calculated/observed. Hence, only the candidates included in the critical flow path (i.e. path that feeds the affected nodes) are considered in the optimisation problem.

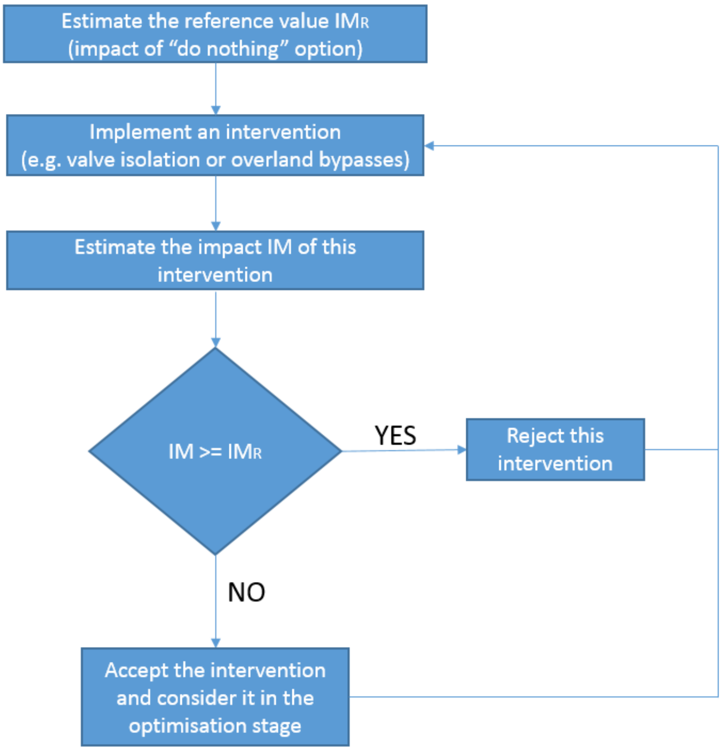

Figure 2-10: Offline assessing process for feasibility of all the possible single interventions (followed in Herman et al. 2018)

After reducing the initial population, NSGA II for the finally identified candidates is implemented and a Pareto set of solutions is identified and presented. The axes of the optimisation are the two objectives (i.e. the impact and the cost). The first objective regards the impact of different combinations between the feasible candidates (i.e. feasible valve isolations and feasible overland bypasses) and the PRV(s). The second objective is associated with the cost of these combinations.

This methodology was tested and verified on the small real-life network of C-Town (Marchi et al. 2014). The result was a Pareto set of optimal solutions. From this set, the authors suggested a potential optimal recovery option that could be proposed to the operators. According to the authors, the application on the case study showed that the proposed methodology is effective and can be applied in near real-time. It provides the operators with a set of optimal solutions and it is them that decide how to respond to the failure. Thus, the methodology could potentially be a part of a DSS.

However, it was only tested on a simple network. Application of NSGA II on more complicated real-life networks, even after reducing the initial population, is expected to be time-inefficient (i.e. not able to identify solutions in near real-time) (Keedwell & Khu 2006; Kang & Lansey 2012). To address the issue of NSGA II inefficiency in real-life networks, different heuristic and meta-heuristic methods have been proposed in the literature. Some examples include Halhal et al. 1997, Tolson et al. 2009, Keedwell & Khu 2006, Kang & Lansey 2012, Bragalli et al. 2012, Zheng et al. 2014 and Gonçalves et al. 2014. However, all these examples regard the optimisation of WDS design. Hence, in the present work a heuristic optimisation method is proposed for optimisation of restoration measures (i.e. operational interventions) to address the above issue.

Paez et al. (2020), in their summary paper, presented several integrated methods for the response to WDS events after an earthquake disaster (i.e. they considered real-life and complex pipe network failures). Later, Zhang et al. (2020) proposed an integrated optimisation-based framework to maximise resilience of a WDS after a disaster-type event (e.g. earthquake). However, both these studies identified the optimum set of response interventions that includes pipe repair or replacement only (i.e. without proposing different types of response interventions). This limitation is circumvented in this thesis by developing a methodology that utilises multiple intervention types (e.g. rezoning, water injection) and that also enables identifying the best time for their implementation in the field in order to restore supply.

Table 2-2: Aggregated table with information about each stage of the Recovery process

Reference	Description
Kapelan et al. (2006)	**Recovery stage** Event impact assessment **Methodology** Risk-based analysis. Extended period simulation. Pressure-driven modelling by Giustolisi et al. (2006). Impact measured in undelivered water demand. Failure probability rate by Bernardi et al. (2005). **Case-study**

	Tested on a simple real-life network (Apulian town in southern Italy). **Pros/cons of method** Method potentially used to support repair planning decision making. Method potentially used for evaluating the expected reduction in risk due to pressure management or rehabilitation. Method fast for near real-time decision-making for repair activity or rehabilitation/renewal planning. Method not considering different impact aspects (i.e. only undelivered water demand). Method not tested on more complex real-life networks. No discolouration potential estimated in impact.
Kao & Li (2007)	**Recovery stage** Event impact assessment **Methodology** Risk-based analysis. Extended period simulation. Pressure-driven model by Gupta & Bhave (1966). Impact measured in undelivered water volume. Failure probability rate by Walski and Pelliccia (1982). Optimisation method (ILOG 2002) for identifying optimal pipeline replacement. Optimisation objective is to maximise the improvement in the water supply reliability in all pipe segments after replacement. Optimisation decision variables are the status (i.e. with failure or not) of each segment. Optimisation constraints include the failure rates definition and cost restrictions of the replacement. **Case-study** Tested on a hypothetical network and a real-life network (Sanchung area in Taipei City). The hypothetical network is simple and the real-life is more complex. **Pros/cons of method** Segment-based models used in replacement/repair decision-making improve water supply reliability. Segment network can be beneficial in other ways too, e.g. in monitoring location siting, partitioning management zones, pipeline network design or expansion. Not appropriate for near real-time decision making on pipe repair/replacement due to long process of identifying segments, especially in complex real-life networks. The impact assessment considered only one impact aspect, i.e. the undelivered water volume and no other impact aspects, including discolouration potential.
Giustolisi et al. (2008)	**Recovery stage**

	Event impact assessment **Methodology** Impact assessment analysis. Extended period simulation. Pressure-driven model by Todini (2003). Impact measured in undelivered water volume. **Case-study** Tested on an artificial network and a real-life network (Apulian town in southern Italy). The artificial network is simple and the real-life is more complex. **Pros/cons of method** The proposed algorithm is novel in identifying topological network changes. Method useful for managing planned and unplanned interruptions to the water supply. The case-study did not present potential of the new method to be applied in near real-time decision-making on response to water network failures.
Beuken et al. (2008)	**Recovery stage** Event impact assessment **Methodology** Quantitative risk analysis. Extended period simulation. Risk/impact measured in water quality index. **Case-study** Tested on a Dutch water network retrieving customer complaints related to water quality in the period 1993 to mid 2005. **Pros/cons of method** Development of a method for the assessment of water quality based on real data, i.e. customer complaints. Time inefficiency due to numerous manual data conversions required for the quantitative risk analysis.
Bicik et al. (2009)	**Recovery stage** Event impact assessment **Methodology** Impact assessment analysis. Extended period simulation. Pressure-driven analysis and value tree by Michaud & Apostolakis (2006). Impact measured in different performance indicators. **Case-study** Tested on a large real-life network (Apulian town in southern Italy). The real-life network is large and complex. **Pros/cons of method**

	The impact model considers discolouration risk through evaluating the risk-trees-based model by Dewis & Randall-Smith (2005). The impact model evaluates impact from the operational perspective (i.e. short-term), e.g. short-term failures caused by pipe bursts allowing better prioritisation of decisions in the operating room. The method provides insight regarding the proper evaluation of negative impact of WDS failures, but there is no evidence in the paper that it can be used in near real-time decision making.
Diao et al. (2016)	**Recovery stage** Event impact assessment **Methodology** Risk-based analysis. Extended period simulation. Epanet engine called via computer program in C# for hydraulic simulations Impact measured in in ratio of unsupplied demand to the total demand. **Case-study** Tested on four real-life network. The real-life networks are relatively small and not complex. **Pros/cons of method** Focus of the method on the failure modes that stress the system rather than the threats. The method can identify the range of impact under different scenarios. The method is more appropriate for strategic system assessment/enhancement rather than real-time impact assessment, because the main aim is to assess/enhance system resilience in the long term. The impact assessment considered only one impact aspect, i.e. the undelivered water volume and no other impact aspects, including discolouration potential.
Qi et al. (2018)	**Recovery stage** Event impact assessment **Methodology** Impact assessment analysis. Steady state hydraulic simulation. Pressure-driven analysis by using equation of Wagner et al. (1988). Impact measured in six hydraulic and water quality (i.e. including discolouration potential) related metrics. **Case-study** Tested on two simple real-life networks and one complex real-life network. **Pros/cons of method**

	The method can provide guidance for effective event management and restoration planning strategies in a water utility. The method can benefit government departments in designing effective management planning when natural disasters occur. The method is more appropriate for strategic (i.e. long term) rather than real-time response planning to a network event, due to the fact that its focus is to provide a good understanding of network properties after analysing different break scenarios which run offline.
Jeong et al. (2006)	**Recovery stage** Event interventions **Methodology** Optimisation analysis (B&B, GA) and heuristics (PBM, WBM, PWBM). Optimisation objective is the minimisation of negative impact of water shortage to the customers. Optimisation decision variables are the proportion of water demand satisfied for each customer node. Optimisation constraints consider hydraulic feasibility. Impact measured implicitly in impact severity. **Case-study** Tested on two small hypothetical network and one large real-life network. **Pros/cons of method** The method can be applied in near real-time for small networks. If the solution of heuristic is included in the initial population of GA, then GA solution time is accelerated. The network models include only one pressure zone. Impact assessment does not consider discolouration potential.
Jeong & Abraham (2009)	**Recovery stage** Event interventions **Methodology** Optimisation analysis (NSGA II). Optimisation objective is the minimisation of negative impact of water shortage (for each customer type). Optimisation decision variables are the degrees of impact of a selected water rationing plan (for each customer type). Optimisation constraints consider hydraulic feasibility. Demand-driven model. Impact measured implicitly in impact severity. **Case-study** Tested on one large real-life network, Epaville. **Pros/cons of method**

	The proposed methodology could be applied under other extreme water network events, such as large-scale pump or pipe failures/bursts. Three different types of customers are assumed in this study: residential, industrial and critical customers. Impact assessment does not consider discolouration potential. The method cannot be applied in near real-time.
Turner et al. (2012)	**Recovery stage** Event interventions **Methodology** Optimisation analysis (Optimization package CPLEX 12.3). Optimisation objective is the minimisation of the sum of the costs of not providing the required demand. Optimisation decision variables are the degrees of impact of a selected water rationing plan (for each customer type). Optimisation constraints consider hydraulic feasibility. Impact measured in volume and transportation cost. **Case-study** Tested on three skeletonized real-life networks. **Pros/cons of method** The method has the potential to support utilities in decision-making on security improvements. The method contributes to controlling the computational time through the new optimisation relaxation/linearization methods. The method assumes static demand patterns. The cost indices have been calculated based on high level of abstraction. Impact assessment does not consider discolouration potential.
Vamvakeridou et al. (2010)	**Recovery stage** Event impact assessment & Event interventions (Integrated response methodologies) **Methodology** Optimisation analysis (Heuristic based on Discrete Dynamic Dimensioned Search). Optimisation objectives are the minimisation of negative impacts to customers and the number of interventions. Optimisation decision variables are the intervention types (i.e. opening valves connecting two different DMAs, modifying the exit pressure from PRVs and setting an overland bypass between fire hydrants). In the impact assessment pressure-driven analysis and hierarchical aggregation are used. Impact measured in different PIs, including discolouration potential. **Case-study** Tested on a large network in North Yorkshire.

	Pros/cons of method The method proposes an integrated decision support system for response to water network failures. The method can provide near real-time decision-making support due to the offline extensive pre-processor. The linguistic preferences for the impact indicators were obtained by a questionnaire distributed among employees of the company and may be a long complicated work/process to apply in water utilities.
Mahmoud et al. (2018)	**Recovery stage** Event impact assessment & Event interventions (Integrated response methodologies) **Methodology** Optimisation analysis (NSGA II). Optimisation objectives are the minimisation of negative impact to customers and the number of interventions. Optimisation decision variables are the intervention types (i.e. opening isolation/rezoning valves, modifying the exit pressure from PRVs and setting an overland bypass between fire hydrants). In the impact assessment pressure-driven analysis is used. Impact measured in undelivered volume of water. **Case-study** Tested on a small real-life network (C-Town) **Pros/cons of method** The method proposes an integrated decision support system for response to water network failures. The method can provide near real-time decision-making support in small networks due to the offline and short online selection of initial optimisation population. The method has not been tested on large real-life networks and hence it is expected that in such case it cannot provide near real-time support.
Paez et al. (2020)	**Recovery stage** Event impact assessment & Event interventions (Integrated response methodologies) **Methodology** Optimisation analysis (NSGA II, heuristic methods, combination of above). Optimisation objectives are the minimisation of negative impact measured in six different metrics. Optimisation decision variable is the status of isolation valves (i.e. open valve means repaired/replaced pipe). In the impact assessment pressure-driven analysis is used. Impact measured in six metrics related to system functionality and time/magnitude of supply interruption. **Case-study**

	Tested on a large real-life network (B-City). **Pros/cons of method** The study presents several different approaches of restoring a water system after an extreme natural disaster contributing to near real-time (in some approaches) decision-making. The study identifies the optimum set of response interventions that includes pipe repair or replacement only (i.e. without proposing different types of response interventions). Discolouration potential is not considered in the impact assessment.
Zhang et al. (2020)	**Recovery stage** Event impact assessment & Event interventions (Integrated response methodologies) **Methodology** Optimisation analysis (GA-based dynamic optimisation method). Optimisation objective is the maximisation of resilience. Optimisation decision variable are the status of pipes or tanks that need to be repaired. In the impact assessment pressure-driven analysis is used. Impact measured in resilience **Case-study** Tested on a large real-life network (B-City). **Pros/cons of method** The benefit of the proposed optimization method is that the total number of the decision variables (damaged elements) and the decision variables themselves can both vary when the hydraulic status of the WDS is updated. The new method can be beneficial to practitioners, water utilities, and relevant government departments by supporting them on the decision-making on natural disasters, such as earthquakes, floods, and typhoons. The study identifies the optimum set of response interventions that includes pipe repair or replacement only (i.e. without proposing different types of response interventions). There is no evidence in the paper that the new method can be used in near real-time. Discolouration potential is not considered in the impact assessment.

2.4 Gaps in knowledge

This section presents the gaps in knowledge identified based on the above literature review. The gaps regard the Event response methodology of both the UU practices and the academic literature. The identification of these gaps will form the basis on which an effective and efficient response methodology will be proposed. The list of the gaps identified include:

- Need to develop an *overall decision support framework* for effective near real-time management of events with focus on the response stage. Although several discreet methodologies for each Event response stage have been proposed, only few studies have developed integrated Event response methodologies to support decision-making and also to interact with operators in near real-time. For instance, Jun & Loganathan (2007) developed an Isolation methodology, Bicik et al. (2009) proposed an Event impact assessment methodology and Jeong & Abraham (2009) presented an Event interventions methodology. Only Vamvakeridou et al. (2010) and Mahmoud et al. (2018) presented overall Event response methodologies (with focus on the Recovery stage). This issue is addressed in the present thesis by proposing an overall response methodology, which supports and guides the operator throughout the entire response process (from detection and localisation of a failure event to implementation of the response interventions in the field) whilst allowing the operator to have a final say. The conceptual framework of the proposed methodology is also based on the interaction with the operator in near real-time by allowing operators to propose/assess different 'what-if' scenarios without being hydraulic experts.
- Need to develop *improved methods for impact assessment* in the context of real-time response. This includes developing models that are able to (a) better quantify the reduced water consumption in event affected parts of the network. The better quantification could involve models that assess the impact in terms of time of lost water, as proposed for example by Kumar et al. (1999) and indicated in the related regulators, and not of volume of lost water. Models for impact assessment could also (b) address other aspects/dimensions of the impact, such as impact on 3rd parties or impact included in other PIs (see e.g. in Bicik et al. 2009) or impact estimation on customers with different vulnerability (see e.g. in Jeong et al. 2006 and Jeong & Abraham 2009). Such impact aspects are not taken into account, for instance, in the latest integrated Event response methodology proposed by Mahmoud et al. (2018). The present thesis proposes

improved impact assessment using realistic impact indicators that cover different aspects of the event. These indicators are also consistently calculated for every proposed response intervention (to facilitate easy comparison between different response interventions).

- Need for *consideration of the discoloration potential* into the impact assessment process. Discolouration is regarded of great importance for both customers and water utilities. It is associated with the quality of water in our taps, which affects our health and safety. It is also the main water quality indicator during failure events in utilities, because it is linked to customer complaints. Water utilities aim to provide high customer service and avoid customer complaints, due to ethical reasons but also due to regulators guidelines. As reviewed earlier in this chapter, Mahmoud et al. (2018) who developed an overall response methodology did not take discolouration aspect into account during the impact assessment process. On the other hand, the rest of the methods reviewed earlier which discussed the discolouration impact aspect (e.g. Qi et al. 2018, Bicik et al. 2009, Beuken et al. 2008), did not incorporate it in an integrated response strategy. This issue is addressed in the present thesis by proposing a discolouration method/model (based on previous work/literature) to calculate the increase in discolouration potential in the context of an overall response methodology.
- Need to develop improved methods for more *realistic selection of operational interventions* that (a) are driven by actual intervention costs rather than surrogate measures (such as number of interventions proposed by Vamvakeridou et al. 2010 and Mahmoud et al. 2018). This will require developing suitable cost models for a range of possible interventions. These methods should also (b) take into account various operational requirements (e.g. duration of injection from overland bypasses, etc.). Finally, (c) consideration should be given to operational interventions not previously addressed in the literature. For instance, in Vamvakeridou et al. (2010) and Mahmoud et al. (2018) only three options of interventions are taken into account. The aforementioned needs are covered in the present overall response methodology by proposing potential interventions (and combinations of them) to implement on the

field based on the real costs of interventions. The proposal of the intervention plan also considers the duration of the interventions implementation on site (i.e. through the cost of employees' working hours) making the selection of the final intervention plan more realistic. Finally, novel intervention types are used such as water injection from water trucks, apart from those already considered in the previous literature (e.g. rezoning and valve manipulation).

- Need to develop *improved optimisation method* in the context of real-time response. Based on the reviewed literature, it was shown that NSGA II is not appropriate for real-life and complicated systems if a near real-time response is required. This is due to the randomly generated initial population which although increases population diversity, it slows down the optimisation convergence. It is also due to the long time it takes to complete a single hydraulic evaluation of a complex network. To this end, alternative methods are required, e.g. heuristic methods, to identify near optimal response solutions in near real-time, even in complex real-life systems. In this work, a novel, heuristic-based optimisation method is proposed, which is able to identify near-optimal solutions in near real-time, both in simple and in complex, real-life networks.
- Need to develop methodology that can support effective *exploration of operator preferred responses* (i.e. manually created responses), in addition to the more automated ones. This involves identification and development of different 'what-if' type scenarios and related modelling support. An example of interaction between the automatic process of impact estimation and the manual process of decision-making by operators for the Event response is the AHP, e.g. proposed by Vamvakeridou et al. (2010), which however does not produce/present to the operators potential response solutions to enable a more efficient decision-making. In the present response methodology, operators are allowed to manually propose their desired response solution based on their preferences/experience (along with the automatically proposed solutions in a different step of the methodology) and assess its end-impact and cost. This novel interaction with the operator in near real-time takes

place via the proposed tool (e.g. allowing operators to propose/assess different ‘what-if’ scenarios without being hydraulic experts).

2.5 Summary and Conclusions

In the present chapter, a literature review on the response stage of the general event/incident management process was carried out. In the context of this, two procedures were discussed: the Emergency management in section 2.2 and the Event management in section 2.3. The Emergency management in section 2.2 reviewed the real-life procedures followed by the industry in case of emergency. It was stated that Emergency management is an integral part of the business plan of every kind of industry, which enables the coordination of actions in case of emergency events, in order to eliminate the negative consequences. In this section, the sub-sections of Emergency management in water systems, in UU and in other infrastructure systems (i.e. Urban security and Oil & gas) were discussed.

The Event management in section 2.3 reviewed the academic literature related to the management of failures in WDSs, such as pipe bursts and equipment failures. The main focus was on the stage of Event response, while a less thorough review of the first two stages (i.e. Event detection and Event localisation) was carried out for completeness. In section 2.4, a discussion was made around the gaps in knowledge so far, which are expected to form the basis for the proposed response methodology. Finally, the present section targets at summarizing the above sections and concluding to some basic points.

Based on the literature review presented in this thesis, the following conclusions are drawn:

- Most of the studies related to the development of a response methodology address separately the Event response stages (i.e. Isolation and Recovery). These studies do not aim to provide integrated methodologies on how to respond to water network failures. They aim to develop numerical methods to address individually the phases of the overall response process. Only a few studies presented an integrated response methodology. In these studies, existing Isolation methodologies were coupled with the proposed Recovery methodologies for the development of an overall response management procedure.

- The Event impact assessment methodologies found in the reviewed papers mostly quantify the impact in terms of volume of lost water. However, not extensive literature proposes the impact assessment in terms of time of lost water, as the related water regulators do. Additionally, more extensive work should be carried out in considering as many PIs as possible stated in the water regulators, such as impact on 3rd parties or impact estimation on customers with different vulnerability.
- Although models for the discoloration potential estimation have been developed, they have not been incorporated in some of the integrated Event response methodologies.
- In the latest integrated Event response methodologies a specific number of intervention options has been proposed. However, in real-life more interventions are applied during the response to an event. The selection of the optimal interventions is also carried out minimising the number of interventions and not considering the actual intervention costs, which would be of more interest for the water industry.
- Only a few studies have developed response strategies where the operators interact with the control system in near real-time. Moreover, in these studies the operators receive information about the impact of the proposed interventions, without the ability to propose their desired response solutions (i.e. ‘what-if’ scenarios) to enable a more efficient decision-making.
- The visualisation tools used so far in the integrated Event response methodologies are the GIS, presentation of possible solutions through a Pareto-style figure and aggregated tables where the partial impact indicators and the overall impact is presented. However, no visualisation tool has been developed to couple the impact assessment with a list of possible solutions (based on ‘what-if’ scenarios and automatically generated optimal responses) in order to enable an efficient response.

3 RESPONSE METHODOLOGY

3.1 Introduction

The water industry faces considerable challenges in making effective use of hydraulic models and sensor data that is collected in WDSs in near real-time (typically every 15-30 minutes). This data and models are still not used much in a water utility's control room, especially when it comes to identifying a suitable strategy to respond to failure events in near real-time. Relevant academic work has not adequately addressed this challenge mainly due to the focus on specific stages (i.e. isolation, impact assessment or intervention) rather than the overall response process. Furthermore, for an effective near real-time response there is still a need to develop: 1) improved impact assessment methods that are based on realistic metrics used in the water industry and that are also used in a consistent manner to facilitate easy comparison between different response interventions, 2) better informed and realistic selection of response interventions to be implemented (e.g. based on operational costs, availability of different types of interventions, etc.) and 3) effective interaction with the control room operators that takes into account their expert judgement, preferences and experience.

In this chapter, a novel response methodology that aims to fulfil the above needs is proposed. The proposed response methodology is implemented via the IRPT, as mentioned in the Introduction. The IRPT is used to guide/support operators in identifying an effective response solution (i.e. a particular response intervention or a set of response interventions). The main aim of this chapter is to show the potential of the IRPT to improve utilities' current practice by supporting/guiding operators in the identification of low end-impact (i.e. the total negative impact after implementation of the response solution) and low cost response solutions.

The chapter is organised as follows. First, in section 3.2 the current practice response methodology in UU and other water industries is described. Then in section 3.3 the response methodology concept, impact assessment, optimisation method and modelling are discussed. In section 3.4 the decision-support tool is illustrated. Finally, in section 3.5 the summary of the present chapter is discussed.

3.2 Current practice response methodology

Different utilities deal with events in a different way and use more or less structured approaches. This section briefly describes a response methodology mainly based on ad-hoc response interventions and that can be considered typical for the UK water sector. In this methodology, the response interventions are largely based on the experience and expert judgement of control room operators, despite various systems are used by the operators to support their decisions. The current response process described in this section has derived from personal interaction of the author of this thesis with people from UK industry (i.e. UU), and it is not found in the literature.

The detection of an event in a water utility is nowadays usually done in two possible ways: a) through customer calls (i.e. reporting no water/low pressure/discolouration/etc.) and/or b) through an automated detection system (i.e. alarms generated based on flow and/or pressure data). Once the detected event is confirmed and approximately localised (e.g. roughly based on customer calls' addresses and/or using other semi-automated means), the utility typically mobilises some available water trucks, called Alternative Supply Vehicles (ASVs). This is done as an immediate restoration measure after an impact assessment usually carried out manually and/or with limited hydraulic model support. Here, an assessment involving the calculation of the water volume required to be supplied per hour (and hence the number of ASVs required per hour) based on the affected DMAs normal water demand may also be carried out.

At the same time, in the control room, after further manual (e.g. by checking service reservoirs' levels using online systems) and/or hydraulic-model-supported initial impact assessment, operators request isolation of the event. Isolation is then carried out either as soon as possible (e.g. if the service reservoirs' levels are quickly dropping or there is significant third-party damage) or later in the day, depending on severity/time of the event and other factors. There are also occasions, where the repair can be conducted without isolating the failure (i.e. under pressure). This occurs in cases of small pin-hole leaks on a section of a small-diameter pipe, where simple patch clamps or special pin-hole leak repair clamps can be used for repair without shutdowns. If isolation is required, the isolation valves are usually identified manually - as the closest operable valves to the event. With some ASVs already on site (or not), the control room operators then attempt to identify the most suitable response intervention or set of response interventions (e.g. how many more ASVs should be sent to the site, a suitable rezoning plan, overland bypasses, etc.) to be implemented while the repair is being carried out. Online map systems, offline connectivity maps, calculation sheets and hydraulic models can be used by the operators for this purpose. The current practice response methodology followed by water industry nowadays can be seen as a flowchart in Figure 3-1.

Bearing in mind the above, it is worth stressing that despite using hydraulic models for some of the aforementioned activities can be considered as common practice, hydraulic analysis is not always carried out thoroughly. This is due to limitations in terms of the time that can be dedicated to this activity, the skills required to run hydraulic simulations, the ability to only test a few scenarios and the difficulty to consistently assess their end-impact.

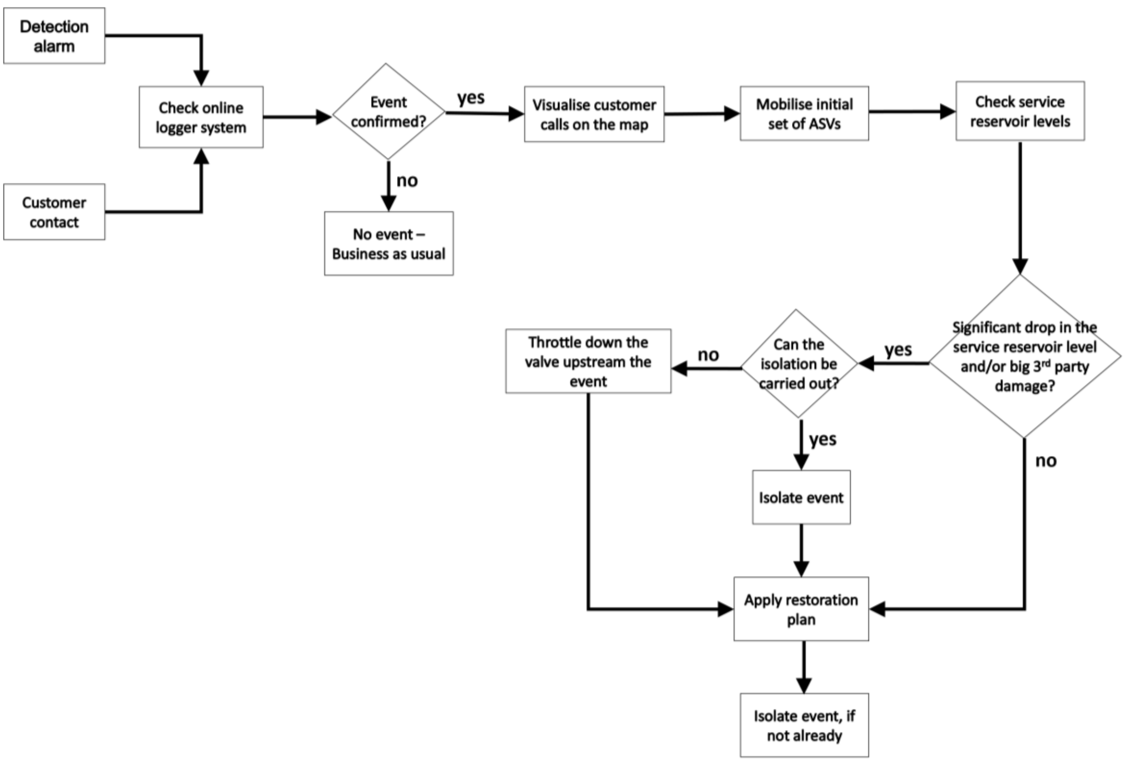

Figure 3-1: Current practice response to water network failure events, typical in UK water industry

3.3 New response methodology

3.3.1 The concept

The new response methodology proposed in this thesis consists of the following main steps: Step 1) initial impact assessment, Step 2) identification of the isolation plan, Step 3) manual identification of a response solution proposed by an operator, Step 4) automatic identification of a response solution generated using optimisation, and Step 5) identification of the response solution to be implemented in the field. These five steps do not need to be necessarily carried out in a sequential manner as presented here. The proposed response methodology's steps are described in more detail subsequently and are also shown as a flowchart in Figure 3-2.

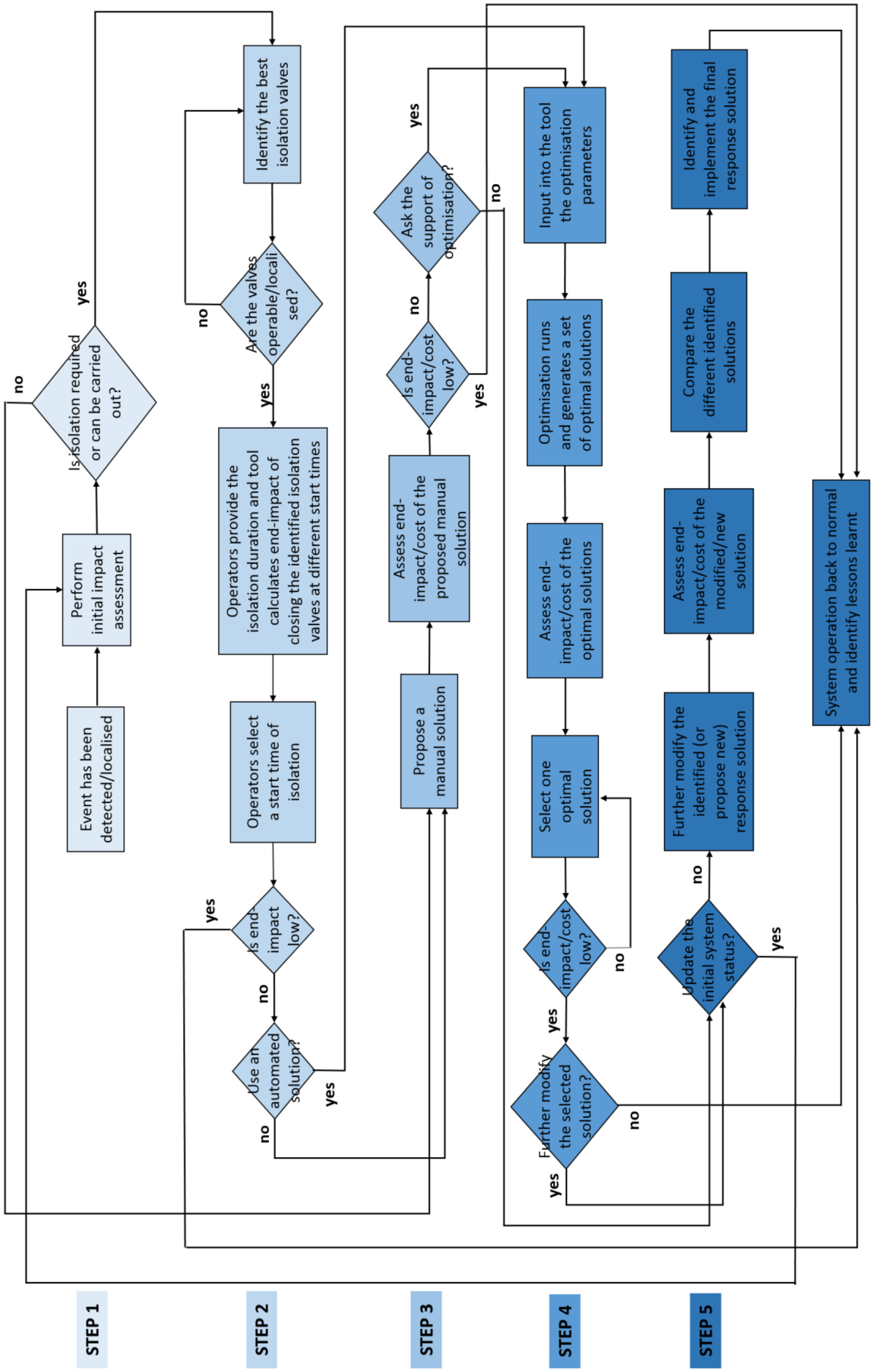

Figure 3-2: New response methodology’s steps

Step 1. Before the proposed response methodology is initialised via Step 1, the utility has already confirmed and localised the event. Hence, knowing the location of the event, an initial impact assessment is performed in Step 1 assuming the ‘do nothing’ scenario. The impact assessment in this step is carried out for the initial condition of the system. The initial condition of the system assumes no intervention in the network to restore the supply. The initial impact assessment enables operators to gain a view of the system’s resilience, i.e. how long the system can operate normally (i.e. supply water to the customers) after the event detection/localisation and before it gets affected due to the event. This step could automate the initial impact assessment in utilities currently carried out manually. In the manual initial impact assessment, operators right after the event confirmation check the service reservoir levels (see flowchart in Figure 3-1). During this process they make manual calculations to estimate the system’s capability to supply water before the reservoir gets empty. However, this process includes time-consuming manual calculations delaying the identification of the best response plan in near real-time. Hence, response methodology’s step 1 facilitates quicker, more precise and more effective (i.e. via known impact indicators, see sub-section 3.3.2) estimation of the system’s initial condition. As soon as the initial impact assessment has been completed, the operators are asked if isolation needs to take place or if it can be carried out. The two following options can then be applied:

a. If isolation can/needs to take place, the operators create an event isolation plan in step 2.
b. If isolation cannot/does not need to take place, they move to step 3 to propose a manual solution.

Step 2. This step includes the identification of the best isolation plan. It is stressed that the decision to implement isolation or not is still manual/human-based, because it is dependent on factors that a computer cannot consider (e.g. whether isolation valves are accessible, operable or can be localised, whether there is contaminated field in the surrounding area, etc.). For the identification of the isolation plan, the best (i.e. closest to the event) set of valves is automatically provided to the operators by the IRPT and the operators are then asked if they are satisfied with this set (e.g. if the identified valves can been localised and/or are operable). If they are not satisfied, they ask the IRPT to automatically provide the next best set of isolation valves. This process is repeated until the IRPT proposes the best possible set of valves (i.e. closest valves to the event that can be localised and operate). As soon as the best set of isolation valves is selected, the operators input into the IRPT the isolation duration and different potential isolation start times. Then, the IRPT automatically calculates the end-impact of the different isolation start times and these are presented to the operators. In view of the calculated end-impacts, the operators can then select a desired start time of isolation. Once the isolation plan (i.e. set of isolation valves and isolation start time) is finalised, the operators are asked if they consider the resulting end-impact (i.e. individual impact indicators) low. It is stressed here that ‘low’ and ‘high’ end-impact is judged by operators. Operators are more likely to judge as ‘low’ or ‘high’ one individual impact aspect, rather than the aggregated end-impact, because individual impact indicators are more comprehensible to them. Additionally, for the individual impact indicators (used in practice) there are thresholds specified by water regulators. Then the two following options can be applied:

a. If they consider the end-impact low, they proceed with the implementation of the ‘isolation only’ final solution without applying any further intervention. Once repair/isolation is completed the system returns back to its normal operation.
b. If they consider the end-impact high (or isolation is not possible), they identify the more comprehensive response solution as follows. The operators are asked if they want the IRPT to automatically generate an optimal solution. The two following options are possible:
    i. If they prefer an automatic solution, they move to step 4.
    ii. If they do not prefer an automatic solution, they proceed by proposing a manual solution in step 3.

<u>Step 3</u>. In this step, the operators are able to propose manual solution(s) by interacting with the IRPT. Here they are enabled to generate several response solutions (i.e. ‘what-if’ scenarios), which include the combination of interventions of their preferences. This could be applied in small-scale/low-impact events (e.g. small leaks/bursts without 3rd party damage or many customers affected), where there is no need to identify the optimum solution. Hence, by assessing only a specific number of response scenarios, operators are able to identify a satisfying response solution in a time period of some minutes. In this step, the IRPT firstly

enables the operators to input their desired and available (e.g. accessible/operable) intervention(s) and the start time of this (these) intervention(s). It is stressed that here operators are able to input a desired start time for each proposed intervention (i.e. different start times). It then provides decision support to the operators by assessing and visualising the end-impact/cost of the proposed manual solution. Then the operators are asked if they are satisfied with the end-impact/cost of their proposed manual solution. Two options then are possible:

a. If end-impact/cost is considered low, a final solution has been found. Once repair/isolation is completed (if applied), the restoration plan (i.e. identified manual solution) is revoked and the system returns back to normal operation.
b. If end-impact/cost is considered high, the operators are allowed to modify the identified solution(s) or propose alternative manual solutions and compare their end-impact/cost by moving to step 5 or ask the IRPT to automatically generate an optimal solution in step 4.

Step 4. Operators input into the IRPT all the desired and available interventions, as well as a time range in which the various interventions could start. Then, the optimisation (through a novel heuristic algorithm) runs and near-optimal solutions are automatically generated and assessed by the IRPT in near real-time (i.e. up to 1 hour after event confirmation). It is stressed that unlike the identification of a manual solution in step 3, the proposed optimisation method identifies solutions that start at the same time. This assumption/limitation enables a near real-time identification of optimal solution(s), because the number of decision variable (and hence the search space) is reduced (i.e. only the intervention options are considered as decision variables and not the start time of each intervention option). The result of the optimisation is a Pareto front of near-optimal solutions. Operators are then able to select one (or more) near-optimal solution(s) on the Pareto front (depending on whether or not the end-impact/cost is low). The selected solution is assessed and visualised to them. Finally, they are asked if they wish to further modify this (these) solution(s) manually. Then two possible options can be applied:

a. If they wish to modify the identified optimal solution, they move to step 5.
b. If they do not wish to modify the identified optimal solution, then a final solution has been found. Once the repair/isolation is completed, the restoration plan is reversed and the system returns back to its normal operation.

Step 5. In this step, the operators are first asked if they want to go back all the way to step 1, with modified system state used as a starting point. This is done to account for the fact that the initial condition of the system may have changed in the meantime, e.g. isolation cannot be conducted anymore due to inoperable valves or contaminated field, or magnitude of leak/break is different. If initial condition has not changed, in this step they can further modify a solution from step 3 or step 4, as well as propose new solution(s). Here, the IRPT enables operators to compare all of the identified solutions consistently (i.e. consistent impact metrics) and with support of effective visualisations (e.g. multiple maps in a single window) of the end-impacts and costs. All this enables the operators to select the final solution they wish to implement.

Once the system operation is back to normal, the operators identify the lessons learned.

3.3.2 Impact assessment methodology

Hereunder, the impact indicators and the assessment method of the proposed response methodology are described. The IRPT provides to operators the capability to automatically assess the end-impact (i.e. the total negative impact after implementation of the response solution to the customers) of a proposed solution based on realistic metrics. In the IRPT a consistent framework for end-impact assessment (i.e. same impact metrics calculated for every proposed response solution) is implemented. This facilitates comparison of different response solutions (i.e. in step 5 of the methodology) and enables more informed decision-making. Furthermore, the IRPT allows the operators to perform this comparison without the need for them to be hydraulic model experts.

The impact indicators proposed in this thesis have been developed bearing in mind the UK water industry practice as well as previous relevant literature (e.g. Bicik et al. 2009). Most of these indicators have not been used before in this context (at least in the published literature). The following aspects of end-impact are considered: water supply interruption, low pressure impact and discolouration risk increase impact. More specifically, the following indicators are used: 1) Customer Minutes Lost (CML), 2) Average Minutes Low Pressure (AMLP), 3) Unaccounted for Water (UW), and 4) Discolouration Risk Increase (DRI). AMLP and UW are calculated for different customer types, namely: residential, industrial and sensitive (i.e. schools and hospitals). The impact horizon in the proposed response methodology is the period of time for which the end-impact is assessed. It starts from the detection/localisation time of an event and lasts until the repair is completed (i.e. time period over which restoration interventions can be implemented).

CML is defined as the mean duration customers are without water supply (i.e. equivalent to pressure ≤3m in the main) in a given reporting year. CML is a real-life indicator used in water utilities nowadays and is calculated for every Discrete Pressure Area (DPA) (i.e. discrete areas within a DMA). It is measured in minutes per customer (mins/cust). In this study CML is found as follows:

$$CML\ [mins/cust] = \sum \frac{Cust_{SI}\ X\ Dur_{SI}}{Cust} \tag{1}$$

where: $Cust_{SI}$ is the total number of customers in each DPA affected by supply interruption at least during one time-step (i.e. 15mins) over the impact horizon; Dur_{SI} is defined as the length of time for which properties are without a continuous supply of water in mins – only events with duration ≥ 3 hours are taken into account; *Cust* is the total connected customers at year end (fixed number for each utility).

The AMLP indicator is defined as follows:

$$AMLP\ [mins/cust] = \frac{Cust_{LP}\ X\ Dur_{LP}}{Cust} \tag{2}$$

where: $Cust_{LP}$ is the total number of customers affected by Low Pressure (LP) (i.e. minimum_pressure < pressure < required_pressure, where minimum_pressure is usually considered in UK utilities as equal to 3m and required_pressure as equal to 15m) at least during one time-step (i.e. 15mins) over the impact horizon; Dur_{LP} is the average low pressure impact duration over the impact horizon in mins; *Cust* is the total number of connected customers at year end (fixed number for each utility).

The total number of customers affected by LP (i.e. $Cust_{LP}$) is calculated based on Bicik et al. (2009) as follows:

$$Cust_{LP} = \sum_{i=1}^{N}(Cust_i)\ X \begin{cases} 1 \quad if \;\; P_{min} < P_i(t) < \; P_{req} & \forall t \in (0,T)\} \\ \quad 0 \;\; \text{if}\, P_i(t) < P_{min} \end{cases} \tag{2a}$$

where: *N* is the number of demand nodes in the system; *i* is the demand node; *t* is the simulation time (with assumed time step of 15mins); *T* is the impact horizon in hours; $P_i(t)$ is the pressure at demand node *i* and time *t* (m of head); P_{min} is the minimum pressure in m of head under which there is supply interruption (equal to 3m, as applied in water utility practice); P_{req} is the required pressure in m of head under which there is low pressure impact (equal to 15m, as applied in water utility practice); $Cust_i$ is the number of customers (of all the types) supplied by node *i*.

The average low pressure impact duration (i.e. Dur_{LP}) over impact horizon is estimated as follows (Bicik et al. 2009):

$$Dur_{LP}\ \ [mins] = \frac{1}{Cust_{total}}\ x\ \sum_{t=1}^{T}\sum_{i=1}^{N}\begin{Bmatrix} Cust_i \quad if \quad P_{min} < P_i(t) < \; P_{req} \\ 0 \qquad\qquad \text{if} \quad P_i(t) < P_{min} \end{Bmatrix} * HydStep \tag{2b}$$

where: $Cust_{total}$ is the total number of customers affected by the failure at least during one time-step over given impact horizon *T* and *HydStep* is the hydraulic time-step (i.e. 15mins).

The UW indicator is calculated as follows (Bicik et al. 2009):

$$UW\ \ [m^3] = \frac{900}{1000} X \sum_{t=1}^{T}\sum_{i=1}^{N}\begin{cases} \frac{(D_{i,req}(t) - D_i(t))\ X\ Cust_i}{Cust_{i,count}} & if \;\; P_i(t) < P_{req} \\ 0 & otherwise \end{cases} \tag{3}$$

where: *T* is the impact horizon (hours), *t* is the simulation time (with assumed time-step of 15mins = 900sec); $D_{i,req}(t)$ is the requested demand at node *i* and time *t* in *l/s*; $D_i(t)$ is the delivered demand at node *i* and time *t* in *l/s*; $Cust_{i,count}$ is the number of customers supplied by demand node *i*. Note that the requested water demand may be undelivered due to either complete interruption or low pressure (i.e. pressure < required_pressure).

The DRI is estimated based on a combination of the methods found in Beuken et al. (2008) and Bicik et al. (2009). Beuken et al. (2008), which was also reviewed in chapter 2, suggest to calculate discolouration risk based on minimum and maximum velocities and maximum flow rates. Here, the minimum and maximum flow velocities in an average demand day are calculated with a hydraulic model for each pipe. The same model is used to estimate the largest flow rate for each pipe under the same demand conditions. The DRI under normal condition (i.e. without simulating an event) is calculated in a pressure-driven EPS hydraulic model. Then, a score is assigned to each pipe for each discolouration risk type (i.e. based on velocities and on flow rates), as shown in Table 3-1. Hence, a score of 1 means low, a score of 2 means moderate and a score of 3 means high discolouration risk.

Table 3-1: Method for rating the discolouration risk due to flow velocity and flow criteria (Beuken et al. 2008)

Discolouration risk type	Component	Subcategory	Ranking	Score
Type 1	Flow velocity	LOW	v_{min}<0.05m/s and v_{max}<0.10m/s	1
		MODERATE	v_{min}<0.10m/s and v_{max}<0.25m/s	2
		HIGH	v_{min}≥0.10m/s and v_{max}≥0.25m/s	3
Type 2	Flow	LOW	Q<25m^3/h	1
		MODERATE	Q≥25m^3/h and <50m^3/h	2
		HIGH	Q≥50m^3/h	3

The discolouration risk for every pipe is calculated as the sum of the scores based on both velocity and flow rate. The resulting discolouration risk scores shown in Table 3-2 are grouped in five severity categories (Beuken et al. 2008), i.e. “VERY

LOW" with a total score of 2, "LOW" with a total score of 3, "MODERATE" with a total score of 4, "HIGH" with a total score of 5 and "VERY HIGH" with a total score of 6.

Table 3-2: Discolouration risk score and risk severity categories for every pipe in the network

Severity category	Total Score	Subcategory
1	2	VERY LOW
2	3	LOW
3	4	MODERATE
4	5	HIGH
5	6	VERY HIGH

Once the discolouration risk score for every pipe has been found, the discolouration risk increase for every pipe can be calculated as the difference between the discolouration risk score under 'failure' and normal conditions. The 'failure' condition is defined here as the WDS condition after the occurrence of the event and/or the implementation of the intervention(s). Similarly to the normal condition, the DRI under failure condition is calculated in a pressure-driven EPS hydraulic model which simulates the failure network. The discolouration risk increase is then ranked based on the total score increase, i.e. "NO RISK" with a total score increase equal to 0, "LOW INCREASE" with a total score increase equal to 1, "MODERATE INCREASE" with a total score increase equal to 2 or 3 and "HIGH INCREASE" with a total score increase equal to 4, as shown in Table 3-3.

Table 3-3: Discolouration risk increase severity categories for every pipe

Severity category	Total score increase	Subcategory

1	**0**	**NO RISK**
2	**1**	**LOW INCREASE**
3	**2 or 3**	**MODERATE INCREASE**
4	**4**	**HIGH INCREASE**

Following the calculation of the discolouration risk increase for every pipe in the network, the number of pipes with at least “LOW INCREASE” (i.e. with total score increase equal to 1 or higher) is used to estimate the DRI (based on a modification from the equation in Bicik et al. 2009):

$$DiscRiskIncrease = count_1^{Np}\begin{Bmatrix} Disc_{j,failure} - Disc_{j,norm} \geq 1 & if\ Disc_{j,failure} > Disc_{j,norm} \\ 0 & otherwise \end{Bmatrix} \qquad (4)$$

where: N_p is the number of pipes in the network; $Disc_{j,norm}$ and $Disc_{j,failure}$ are the total discolouration risk of pipe *j* under normal and failure conditions, respectively.

3.3.3 Optimisation method

Optimisation problem formulation

In the present sub-section, the proposed optimisation method used in the response methodology is described and formulated. Initially the optimisation problem (i.e. objective functions, decision variables and constraints) are presented. Then a heuristic-based approach to solve the optimisation problem (i.e. to identify near optimal solutions in near real-time) is discussed. As presented earlier, the IRPT provides to operators the capability to automatically identify a number of optimal solutions (i.e. in step 4 of the response methodology) by solving a two-objective optimisation problem. The two objectives are the minimisation of total end-impact (of a given response solution) and the minimisation of the total cost associated with this solution.

The first objective function is the minimisation of the total (i.e. aggregated) end-impact, i.e. impact after interventions are implemented. This is estimated by normalising and then adding up the values of the individual impact indicators (see sub-section 3.3.2). Before aggregating, the normalised indicators are multiplied with specified weights based on the priority/preferences of the operators as follows:

$$Total\_impact = \sum_{i=1}^{4}(w_i f_i') \quad (5)$$

where *i* is the index of each impact indicator with *i* ϵ [1, 4]; f_i' is the normalised impact indicator *i* and w_i is the weight of impact indicator *i* with $\sum w_i = 1$.

It is stressed here that by assigning weight to each impact indicator, operators in a water utility are able to ‘guide’ the identification of a response solution towards their preferences. Hence, by assigning e.g. a higher weight value to a selected indicator, this impact indicator is significantly reduced (more than the other indicators) in the identified solution. This is important in water utility practice, because operators many times prefer to reduce more one impact aspect for different reasons. For example, if an event occurs in an area with repeated discolouration problems, they may decide to increase the weight of DRI in order the DRI to be significantly reduced (comparing to the rest of indicators). In that way they avoid the customer complaints too.

The impact indicators are normalised in the range [0, 1] as follows:

$$f' = \frac{\mathrm{f} - \mathrm{f}_{\min}}{\mathrm{f}_{\max} - \mathrm{f}_{\min}} \quad (6)$$

where f' is the normalised impact indicator value; *f* is the non-normalised impact indicator value; f_{min} is the minimum impact indicator value and f_{max} is the maximum impact indicator value.

If an impact indicator is equal or includes time, the minimum value is equal to 0 and the maximum value is equal to the maximum value of simulation duration. If an impact indicator is equal or includes number of customers, the minimum value is equal to 0 and the maximum value is equal to the total number of customers in the network under scrutiny. If an impact indicator is equal or includes volume of water, the minimum value is 0 and the maximum value is equal to the total water volume able to be supplied by all the sources in the network under scrutiny. Finally, if an impact indicator is equal or include number of pipes, the minimum value is 0 and the maximum value is equal to the total number of pipes in the network under scrutiny.

The second objective function is the minimisation of the total cost associated with the response solution, calculated as follows:

$$Total\_cost = c_{rez} d_{rez} N_{rez} + c_{PRV} d_{PRV} N_{PRV} + c_{ASV} h_{ASV} + c_{OLB} h_{OLB} \tag{7}$$

where c_{rez}, c_{PRV} are the costs (£) per hour of manipulating (i.e. opening, closing or adjusting) a single rezoning or PRV and c_{ASV}, c_{OLB} are the costs (£) per hour of ASV and Overland Bypass (OLB) injection; d_{rez}, d_{PRV} are the times it takes to open, close or adjust a single rezoning valve or PRV, in hours; h_{ASV}, h_{OLB} are the total durations of ASV and OLB injection (i.e. hours of injection from all the ASVs and OLBs sent to site) and N_{rez}, N_{PRV} are the numbers of rezoning valves and PRVs to open, close or adjust in the specific response solution.

The above unit costs (i.e. c_{rez}, c_{PRV}, c_{ASV}, c_{OLB}) are estimated based on the information obtained from the water utility. For example, in the cost of overland bypasses other factors could be taken into account, e.g. the cost of fuel for the transportation of bypasses to the site as well as other standard fees. However it was chosen here not to do so, i.e. to calculate this cost only based on the hourly cost of injection, because the duration of injection primarily affects the cost calculation. Therefore, the cost function presented above is approximate only, but it can still be used for relative comparison of different solutions during the optimisation process. The cost function shown here can be easily replaced with a more accurate one where additional information is available.

It is highlighted here that the cost function in Equation 7 calculates the cost/expenses of the intervention of the utility (via the intervention measures) to the network under failure. There are other sources of cost/expenses for the utility, such as cost of reputation, customer complaints, undelivered/lost water, etc., that was not counted here for simplification reasons.

The decision variables of the optimisation problem are the status of each operational intervention (i.e. interventions used or not) in a given response solution. At this point it is worth stressing that the term *intervention* here is defined by a specific set of intervention types and locations. For example, one intervention is the ASV injection located at point 1 and a different intervention is ASV injection located at point 2 (i.e. same type but different location). Similarly, one intervention is rezoning from valve 3 (i.e. located at point 3) and a different intervention is rezoning from valve 4 (i.e. located at point 4). The decision on type and location of each intervention occurs at the same point in time, and not in different stages during the decision-making.

The operational intervention types considered in this methodology are: 1) rezoning by valve manipulations (i.e. opening of initially closed boundary valves), 2) water injection at different network locations, 3) overland bypasses and 4) combination of these. Water injection, which is a novel type of intervention considered in this study, is carried out through the ASVs. It is important to stress that rezoning is assumed to last until the repair is complete (i.e. as in utility's general practice) and, hence, its duration is not considered as a decision variable. ASV injection, on the other hand, is carried out until the tank (modelled at each injection point, see above) gets empty. This may happen before the repair is complete, depending on the water demand (under normal conditions) of the affected area.

The intervention of overland bypass (OLB) is a quite common intervention measure in utilities. Overland bypasses bypass water from one unaffected node/area/DMA to another affected node/area/DMA. In practice, they are linked to hydrants and they come to specified diameters and lengths. Hence, in the hydraulic model of this thesis, all the possible OLBs (i.e. with length under 300m) were modelled as additional pipes with initially closed status (i.e. inactive). When/if a response solution requires an OLB to be activated, the IRPT gives the order to the Epanet file to open the status of this OLB pipe.

It is also important to highlight here that the start time of implementation of the interventions is not a decision variable. This implies that the interventions (i.e. types and locations) identified by solving the optimisation problem are implemented at a fixed time. This start time is selected by the operators, who are able to input it in the IRPT. Finally, note that the proposed optimisation method can be used if additional interventions are considered, i.e. the optimisation methodology proposed here is not limited to the intervention types considered here.

The mathematical description of the present two-objective optimisation problem follows:

$$\min f(x) = (Total\_impact, Total\_cost) \tag{8}$$

Subject to: $\boldsymbol{x} = (t_{rez,i}, t_{ASV,j}, t_{PRV,k}, t_{OLB,l}, s_{rez,i}, s_{ASV,j,}s_{PRV,k,}s_{OLB,l}) \in X$ (9)

$i = [1, N_{rez}], \quad j = [1, N_{ASV}], \quad k = [1, N_{PRV}], \quad l = [1, N_{OLB}]$

where: x is the decision variable vector; X is the decision variable space; $t_{rez,i}$ is the start time of rezoning from location point i; $t_{ASV,j}$ is the start time of ASV injection from location point j; $t_{PRV,k}$ is the start time of setting adjustment of PRV located at point k; $t_{OLB,l}$ is the start time of injection from OLB located at point l; $s_{rez,i}$ is the status of the rezoning valve located at point l; $s_{ASV,j}$ is the status of the ASV valve located at point j; $s_{PRV,k}$ is the status of the PRV located at point k; $s_{OLB,l}$ is the status of the OLB located at point l; N_{rez} is the total number of rezoning valves; N_{ASV} is the total number of ASV points; N_{PRV} is the total number of PRVs and N_{OLB} is the total number of overland bypasses.

The optimisation constraints are as follows:

$Total\_impact \leq Total\_impact_{ref}$ (10)

$\sum_{l \in in(n)} Q_l(t) - \sum_{l \in out(n)} Q_l(t) - Q_{n,del}(t) = 0, \quad n \in N$ (11)

$K_l Q_l^{\alpha}(t) = P_u(t) - P_d(t), \quad for\ l = (u,d) \in L$ (12)

$t_{rez,i}$, $t_{ASV,j}$, $t_{PRV,k}$, $t_{OLB,l} \in \{t_{min}, t_{max}\}$ (13)

$s_{rez,i}$, $s_{ASV,j}$, $s_{OLB,l} \in \{s_C, s_O\}$ (14)

$s_{PRV,k} \in \{s_{min}, s_{max}\}$ (15)

where: t_{min}, t_{max} are the min and max time each intervention can start, respectively; s_c is the closed status of the valve, equal to 0; s_o is the open status of the valve, equal to 1; s_{min} is the minimum value of PRV setting; s_{max} is the maximum value of PRV setting; $Total\_impact_{ref}$ is the reference value of total end-impact equal to the total end-impact of the initial impact assessment (i.e. 'do nothing' case) calculated in step 1 of the response methodology; $Q_l(t)$ is the flow rate in link $l = (u,d)$ at time t, $in(n)$ and $out(n)$ are the set of pipes that are supplying to and delivering flow from node n at time t, respectively; L is the number of network links; K_l is the head friction loss coefficient at link l and α is the Hazen–Williams coefficient (α = 1.852).

The optimisation constraint in Eq. (10) ensures that the identified response solution will further reduce end-impact when compared to the 'No intervention' case (or 'do nothing' case). This implies that any proposed solution with total end-impact higher than the reference value is rejected. The optimisation constraints in Eqs (11) and (12) represent the mass conservation and the energy conservation equations for the network. The optimisation constraints in Eqs (13), (14) and (15) define the values that the decision variables of the present optimisation problem can take.

It is stressed here that optimising for minimum end-impact and cost has multiple benefits for a utility. The most important benefit is reducing the impact on the customers which can be costly in many ways (financially but also in terms of reputation, etc.). A couple of other examples related to costs include: 1) operational savings in the long-term as many events may occur each year - although the cost of a single response solution may be small (e.g. hundreds of pounds), and 2) less time spent on site for opening valves or injecting water - this could benefit utilities in terms of more efficient scheduling of the technicians' activities.

It can be noticed from the above that the two objective functions are the total impact and total cost. The total impact, from one hand, is influenced by the individual impact indicators. The different indicators are influenced by the duration of the event/supply interruption, the number of customers affected and the number of pipes with increased risk of discolouration. As far as the cost function is concerned, the optimisation is influenced by the individual costs of the different interventions, and hence by the number and location of these interventions. It can be observed that in all above impact and cost aspects, the level in the tank plays a significant role. The level in the tanks at the moment of the event defines the time the network will continue to supply water, and hence the duration/magnitude of supply interruption (i.e. total impact) and the intervention types (i.e. total cost). Having said this, the control of pumping stations during an emergency could be a significant move to control the tank levels. However, this type of intervention was not considered here, because it is not a common measure of response to pipe bursts in UK water utility practice.

Heuristic-based optimisation method

The heuristic-based optimisation method developed here consists of three main steps, the offline step 0 and the online steps 1 and 2. The offline step is conducted under normal (i.e. business as usual) operation of the system (i.e. no event has been detected/localised). It contains all the (offline) actions required by the utilities to identify their available intervention options (i.e. types and locations) in their system. The online steps (steps 1 and 2) include manual/human decisions and automatic calculations for the preparation of the optimisation and the optimisation through a heuristic algorithm, respectively. In Figure 3-3 the optimisation steps and the heuristic algorithm are shown.

Step 0: Offline: Update database with available interventions

Step 1: Online: Preparation for optimisation

a. Initial narrowing-down of interventions

b. Individual evaluation of end-impact/cost of single interventions

c. Selection of the final number of interventions

Step 2: Online: Optimisation (heuristic algorithm):

a. Assess end-impact/cost of the initial solution m (i.e. IM_m, C_m). Go to step 2b.

b. Assess end-impact/cost of the subsequent solution i (i.e. IM_i, C_i). Go to step 2c.

While $i \leq i_{max}$

*c. **If** $IM_m \leq IM_i$ **and** $C_m \leq C_i$, then go to step 2h, otherwise go to step 2d.*

*d. **If** $IM_m > IM_i$ **or** $C_m > C_i$, then go to step 2i, otherwise go to step 2h.*

e. Assess end-impact/cost of the subsequent solution i+1 (i.e. IM_{i+1}, C_{i+1}). Go to step 2f.

*f. **If** $IM_i \leq IM_{i+1}$ **and** $C_i \leq C_{i+1}$, then go to step 2h, otherwise go to step 2g.*

*g. **If** $IM_i > IM_{i+1}$ **or** $C_i > C_{i+1}$, then go to step 2i, otherwise go to step 2h.*

*h. Reject solution, **i = i +1** and go to step 2e.*

*i. Accept solution, **i = i +1** and go to step 2e.*

End of iterations

j. Identification of the final Pareto front of near optimal solutions.

Figure 3-3: New optimisation method steps and heuristic algorithm

The proposed optimisation method's steps are described in details in the following text. Step 0 includes the offline preparation for the optimisation. Here, the initial list of all the interventions is identified. This database of interventions should be updated periodically by the utility to reflect reality. The offline process here, unlike the process in Mahmoud et al. (2018), does not consider any event scenario and hence no hydraulic simulation is conducted for the identification of affected DMAs/nodes. This is due to the fact that when offline, it is impossible to predict/evaluate all the possible event scenarios, including start time of event, start time of isolation, magnitude of leak/burst, location of event, etc.

In step 1, the online preparation for optimisation takes place. Specifically in step 1a, the initial list of interventions from step 0 is narrowed down in the following way: (a) the overland bypasses and rezoning valves located in areas that link affected with unaffected DMAs are considered, (b) the overland bypasses and ASV points located in the affected DMAs are considered and (c) the PRVs located upstream of affected nodes are considered. Hence it is implied that at this step, the affected DMAs/nodes of the specific event have to be identified after hydraulic analysis. In this step, a DMA is affected when at least one node has pressure less than 15m (i.e. low pressure or no supply impact) for at least one time-step (i.e. 15mins). It is stressed that the affected DMAs/nodes and the narrowed-down interventions are identified automatically by the IRPT after running the initial impact assessment. Hence operators in this step have only to manually initialise the initial impact assessment (i.e. by inputting the required information in the tool) and then automatically the affected DMAs/nodes and the narrowed-down interventions are presented to them. This step lasts as long as it takes for a single impact evaluation to run, i.e. from some seconds (in small/simple networks) to some minutes (in larger/more complex, real-life networks).

In step 1b, individual evaluation of end-impact and cost for the narrowed-down interventions (i.e. identified in step 1a) for a selected (by operator) start time is conducted. This step is also conducted automatically by running impact assessment of the aforementioned interventions. The manual process the operators have to follow here is to take the list of the narrowed-down interventions from step 1a and input it in the tool together with the start time of their preference. After the impact assessment of all the narrowed-down interventions, the individual interventions that do not reduce the initial end-impact (i.e. of the 'No intervention' case) are rejected and not considered anymore in the next step. The start time is selected by operator due to time limitation to evaluate every single start time. This implies that all the interventions will be implemented at the same time. This is a significant limitation of the proposed optimisation method, because in practice each intervention occurs at a different time. However, when online, the time to identify the best solutions is limited. The selection of start time by operators compensates this limitation though, as engineering judgement makes this selection more realistic (i.e. time to reach site, availability/accessibility of recourses, etc.). In Mahmoud et al. (2018) the start time of interventions is not a variable either (e.g. for the burst on pipe P307 they consider start time 8 hours after detection for all the interventions).

It is stressed that the heuristic proposed in step 2 (i.e. optimisation step) can be also applied considering the start time of each intervention as a decision variable. The duration of step 1b is equal to the duration of a single impact assessment evaluation (i.e. a number seconds for small networks or a number minutes for larger networks) multiplied with the number of the narrowed-down interventions. For example, for a complex real-life network where a single impact evaluation takes e.g. 3mins and 10 interventions have been identified in step 1b (found to reduce initial end-impact), then step 1b takes 3mins x 10 interventions = 30mins.

In step 1c, a number (hereunder equal to *x*) of interventions (i.e. a sub-set of the interventions identified in the previous step) with the lowest end-impact is selected and these interventions are nominated to the optimisation stage (i.e. next step). This number depends on the time it takes for each evaluation to be completed and the time left for a near real-time response to be conducted. Hence, continuing the aforementioned example (mentioned in the previous paragraph) where 10 interventions were identified in step 1b in a complex, real-life network, then these 10 interventions could be all selected here in step 1c (i.e. x=10 interventions). This is due to the fact that 10 interventions in step 1c (i.e. 10 decision variables for the optimisation in the next step) imply 10 more impact evaluations in the optimisation step (i.e. the optimisation runs as many evaluations as the number of decision variables, see heuristic concept in the next paragraph). This step is completely manual and hence, it takes a number seconds for operators to decide.

In step 2, the optimisation via a novel heuristic algorithm takes place online. The heuristic algorithm is completely automatic and the steps are described hereunder. In step 2a in real-time, an initial solution is identified (from the identified list of *x* interventions in step 1c) by the heuristic algorithm as the single intervention with the lowest cost. If more than one solutions with the same lowest cost exist, then the solution with the lowest end-impact for this cost is selected by the algorithm. Then, the heuristic identifies the subsequent solution *i* in step 2b as the single intervention from step 1 with the lowest end-impact. If more than one solutions with the same lowest end-impact exist, then the solution with the lowest cost for this end-impact is selected by the algorithm. This is done in order to account for the other extreme point, i.e. the solution with the lowest end-impact. Solution *i* is accepted if <u>at least one</u> of the two objectives is better (i.e. lower) comparing to the previously accepted solution (i.e. at this point the initial solution). In step 2e new solutions are identified by combining the remaining single interventions. At every iteration, the single intervention with the next lowest end-impact is added to the previous solution. If the new solution is rejected, then the last single intervention that was added is removed and the next best (i.e. with lowest end-impact) single intervention is added. Iterations (i.e. new solutions generation) end when all the single interventions identified in step 1 have been added/used. Like step 1b, this step's duration is equal to the duration of a single impact assessment evaluation (i.e. some seconds for small networks or some minutes for larger networks) multiplied with the number of the interventions.

It is stressed that the heuristic's checks of end-impact/cost of the subsequent solutions (i.e. steps 2c, 2d, 2f and 2g), do not always generate non-dominated solutions. For example, when both objectives of the subsequent solution are lower than the ones in the previous solution, then the subsequent solution dominates the previous one. This issue is addressed at the end of iterations (in step 2j) by identifying the non-dominated solutions. The non-dominated solutions then form the final Pareto front of near-optimal solutions proposed to operators.

It is also highlighted that the focus of this proposed optimisation method is not on the selection of the initial population, but on the improvement of the optimisation method for the generation of near optimal solutions in near real-time. Hence, the heuristic algorithm proposed here (in step 2) can be easily linked to any preferred method for selection of initial population (i.e. step 1 can be substituted with any desired initial population selection method).

The concept of the development of the heuristic algorithm is based on the creation of the Pareto front curve. On a graph with vertical axis equal to the end-impact (%) and horizontal axis equal to the total cost (£) of a response solution, the Pareto front should have the shape of a concave upward decreasing curve.

Starting from the upper left point of this curve, this point is expected to be the solution with the lowest cost and largest end-impact comparing to the rest of solutions on the Pareto front. Based on this consideration, the initial solution identified in step 2a of the heuristic is the single intervention with the lowest cost (between all the single interventions identified in step 1 of the method). This cheapest single intervention is also expected to obtain the largest end-impact between the rest of Pareto front solutions, because the subsequent solutions will be combinations of single interventions, i.e. with lower end-impact.

The next point on the Pareto front, as we follow the curve from the left to the right, is a solution with lower end-impact and higher cost comparing to the upper left point (i.e. first solution). In the heuristic this point is identified via step 2b, as the single intervention with the lowest end-impact (between all the single interventions identified in step 1 of the method). This solution is expected to obtain lower end-impact and higher cost than the upper left point, but not the lowest one and highest one, respectively. This is because the subsequent solutions (identified via step 2e of the heuristic) include combinations of single interventions, i.e. with lower end-impact and more expensive. The assessment criteria in steps 2f and 2g of the heuristic ensure that each subsequent solution improves (by reducing either end-impact or cost or both) the next one. Then, each subsequent solution is rejected or accepted in steps 2h and 2i, respectively, based on these assessment criteria.

For the purposes of the case studies (see chapter 5), the NSGA II is also conducted in order to point out the error introduced due to the heuristic's limitation. In the NSGA II method the same objective functions and constraints as in the heuristic method are used. The difference between the two optimisation methods lies in the decision variables. Hence, in the NSGA II the decision variables are not only the status of interventions, but also the start time of each intervention. Hence, whereas t_{min}, t_{max} (in Eq. 13) in the heuristic method are equal to each other, in the NSGA II they are different to each other and for each intervention. In that way, in the NSGA II solutions, each intervention can start in a time range and each start time can be different from the others. This consideration makes the NSGA II solutions more realistic/accurate.

The heuristic-based optimisation method described in this section seems to be quite promising in terms of accuracy and computational time based on the results obtained (see Chapter 5). It is an online process, which means that it is implemented after the event has been detected/localised (in step 4 of the response methodology). The online implementation of this method allows operators to input in the tool all the known details of the event (i.e. event start time, burst pipe location, impact horizon duration, weights of impact indicators, location of potentially non-operable valves, start time of interventions, etc.). It is hence noticed that there are many factors that define an event. Simulating all the possible combinations of these factors offline (i.e. when plenty of time exists) in order to simulate different event scenarios might be effective, but only in some cases. This is due to the difficulty of operators to think/predict all the possible scenarios, especially considering that in real-life there are many unpredictable factors (i.e. non-accessible points, non-operable valves, etc.). Additionally, it might be the case that an event occurs which they have not simulated/predicted offline and hence they might waste significant time when online in the attempt to identify the response for this event from their offline database. Hence, an online method, such as the heuristic-based one developed here, which is based on the real data of the event for the identification of an optimum response is more useful for utilities.

3.3.4 The modelling

Pressure-driven model

As mentioned earlier, the proposed response methodology is implemented via the interactive decision-support tool, the IRPT. In the IRPT, the hydraulic simulations are carried out by using EPANET2 (Rossman 2000) and pressure-driven network modelling based on methodology developed by Paez et al. (2018). According to the last study, the pressure-driven network is modelled by adding the following artificial elements to each node, in order: a Flow Control Valve (FCV), a dummy node, a Throttle Control Valve (TCV), another dummy node, a Check Valve (CV) and a reservoir, as shown in Figure 3-4.

In Figure 3-4, the FCV ensures that the delivered flow does not exceed the required demand of the node. Therefore, the flow setting of the FCV is equal to the required demand at the node. The downstream dummy node is added to link the FCV with the downstream TCV. The TCV is used to simulate the pressure-flow relationship when pressure value is lower than the required pressure. This is applied by setting TCV's head loss coefficient based on rearranging Wagner's equation and equating the head loss in the valve with the pressure at the node. After the TCV, another dummy node is added to link it with the CV. The CV does not allow any inflow (i.e. flow towards the node), if the pressure at the node is less than zero. Finally, the reservoir is used to represent the appliances lumped in the demand node, and therefore should not supply any flow. The parameters of the CV are properly set to produce negligible head losses when water is flowing in the right direction (i.e. short length and large diameter). Finally, the elevation of the reservoir is equal to the elevation of the demand node to make sure that there are not additional head losses.

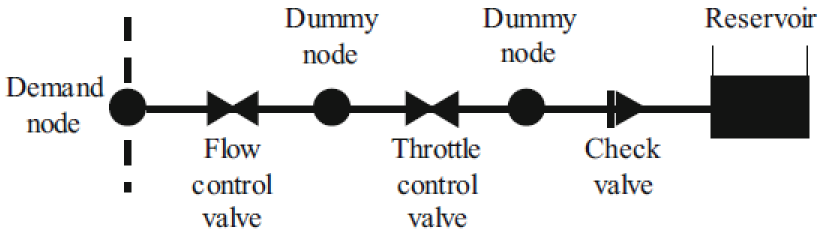

Figure 3-4: Artificial elements connected to each demand node for the pressure-driven modelling proposed by Paez et al. (2018)

The demand-driven analysis conducted by EPANET2 accurately estimates the nodal demands in normal operating conditions, but not in the pressure-deficient ones that occur during various system failures (e.g. during a pipe burst or some equipment failure). Hence, in this study, the original EPANET2 hydraulic model is modified by using the approach proposed Paez et al. (2018). This method works by adding suitably chosen dummy elements to the original EPANET2 model (see Figure 3-4). This creates the pressure driven model that is able to simulate hydraulic conditions in the network under both normal and pressure deficient conditions. The Paez et al pressure-driven method has been selected here as it was thoroughly tested, validated and demonstrated to work effectively on real-sized networks producing accurate hydraulic results (Paez et al. 2018). The use of this model provides additional computational burden for the calculation of different impact indicators, but then so does any other pressure-driven method – this is simply the price to pay for being able to simulate pressure-driven conditions in the pipe network. Finally, note that the selection of a pressure-driven model is not the focus of this study, i.e. any other reliable and accurate pressure driven model can be used instead within the response methodology presented in this project.

ASV modelling

In this study, an ASV is modelled as a tank linked to the injection point (i.e. demand node) through a pump (to manage the pressure pumped into the network) and a valve (to allow water flow from the tank to the system). Usually, utilities dispatch 3 ASVs of $30m^3$ to every injection point in order to guarantee continuous supply to the affected node/customers. In this study, to simplify the coding required in the IRPT, 1 artificial ASV with volume equal to $90m^3$ (i.e. 3 x $30m^3$) is modelled at each injection point. Each artificial ASV tank connects to the ASV point via a dummy TCV (diameter 50mm, setting $5x10^{20}$, loss coefficient 0.5), two dummy pipes (length 1m, diameter 97mm, roughness Darcy-Weisbach 0.15), a pump (pump flow is a function of pump head: for flow=0 litres/sec, head=32m, for flow=20 litres/sec, head=31m, for flow= 40 litres/sec, head=28m) and a tank (elevation equal to elevation of node, initial level 1.5m, minimum level 0m, maximum level 1.5m, diameter 50mm, volume curve is a function of level: for 0m, volume=$0m^3$ and for 1.5m, volume=$90m^3$). The above settings were obtained by the utility and the ASV modelling layout is shown in Figure 3-5.

It is important to highlight that the ASV configuration in Figure 3-5 attempts to resemble the reality. Hence, it is important to model a pump and a specific tank level, because in real-life a specific amount of water (i.e. contained in the tank) is pumped into the system under a specified pressure-flow relation (i.e. given in the pump settings of the ASV).

It is also stressed that the TCV in the configuration of Figure 3-5 plays the role of closing or opening the ASV. Initially, the TCV is closed, which is simulated in the IRPT with a very large value of TCV setting, i.e. very large head loss, (e.g. $5x10^{20}$). Once an ASV needs to be activated, then the IRPT gives the order to the Epanet file to open the TCV by changing the setting to a very small setting value (e.g. 0.5).

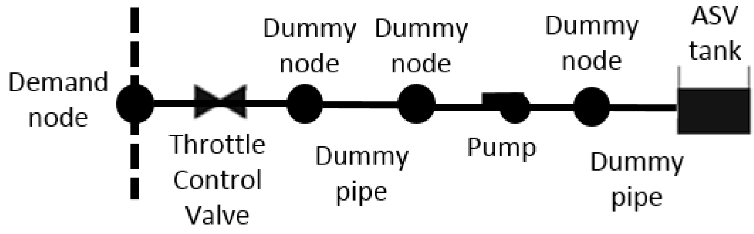

Figure 3-5: ASV modelling in the IRPT

Break/leak modelling

The modelling of a break or leak is carried out based on the methodology used in Paez et al. (2020) by adding the following elements, as shown in Figure 3-6, two dummy pipes, one check valve and one emitter. Based on Paez et al. (2020), the emitter coefficient is $K = 6.07 \cdot 10^{-5} \cdot d^2$ for breaks (d is the diameter of the pipe in millimetres and K is in $L/s/m^{0.5}$) and $K = 3.87 \cdot 10^{-3} \cdot d$ for leaks, while the emitter exponent is $\alpha = 0.5$.

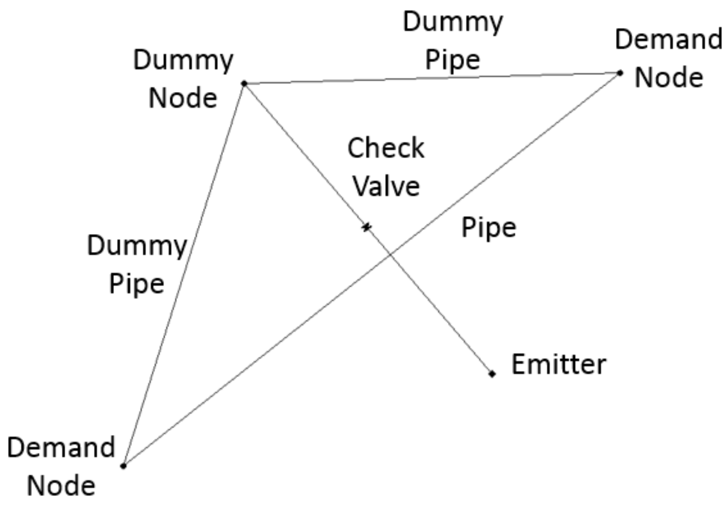

Figure 3-6: Modelling of a break or leak in the IRPT

It can be observed that the emitter coefficient depends on the diameter of the pipe and the event type. For breaks (i.e. significant amount of outflow, usually obvious in the environment) the emitter coefficient depends on the square of diameter. On the other hand, for leaks (i.e. lower amount of outflow), the emitter coefficient depends on the first exponent of diameter. The elevation of the emitter is the average elevation of the elevations of the two demand nodes, because in the model the emitter is connected in the middle of these two demand nodes. Similarly to the node of emitter, the dummy node linked with the emitter through the check valve, also obtains the average elevation of the two demand nodes. The check valve now is used to ensure one direction flow from the system towards the environment (i.e. as in the case of leaks/breaks). The length, the diameter and the roughness of the check valve are such that ensure negligible headloss (i.e. length equal to 0.01, diameter equal to 999, Darcy-Weisbach, D-W, roughness equal to 0.0001). Finally, the two dummy pipes are used to simulate the alternative path of water towards the emitter (i.e. towards the environment) when there is break/leak on the pipe. This is simulated in the model by closing the status of the failure pipe and opening the status of the two dummy pipes. The length of each of the two dummy pipes is equal to the half length of the failure pipe, because as said earlier the dummy node connecting the two dummy pipes is located in the middle of the failure pipe. Additionally, the sum of the lengths of the two dummy pipes should be equal to the length of the pipe, because the model simulates an alternative path (i.e. with the same properties) from the failure pipe. Having said this, the diameter and roughness of the two dummy pipes are the same with the diameter and roughness of the failure pipe.

3.4 The decision-support tool IRPT

The proposed response methodology has also been developed as an interactive decision-support tool, the IRPT. As mentioned in the Introduction, the IRPT is implemented in the programming environment of MATLAB R2016b (Higham et al. 2016). The IRPT links to EPANET 2.0 (Rossman 2000) for the execution of the hydraulic simulations. The IRPT also links to the QGIS software to visualise the spatial distribution of end-impact on a suitable map of the analysed water system. In Figure 3-7, the application of the response methodology via the IRPT is presented.

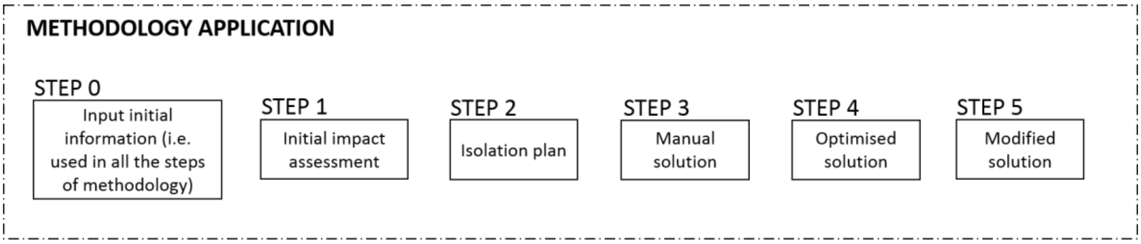

Figure 3-7: Application of the proposed response methodology via the IRPT

As mentioned earlier, the proposed methodology consists of five steps (see section 3.3), as also shown in Figure 3-7. Step 0 is not a methodological step, but is only applied within the IRPT to store some piece of information. For the application of the methodology via the IRPT, a three-stage routine is followed in each of the five methodological steps (i.e. step 1 to step 5): Stage 1) involves obtaining the operators' inputs, Stage 2) involves carrying out hydraulic simulations to assess the end-impact/cost for each solution and Stage 3) involves visualising the calculated end-impact of each solution.

Hereunder the steps shown in Figure 3-7 are explained in more details. In step 0, some general initial information are inputted once in the IRPT and the results are saved in the MATLAB space for use in the latter steps. The initial general input information is shown in Figure 3-8. The pieces of information shown in Figure 3-8 are human-based decisions (i.e. based on operators' preferences/engineering judgement).

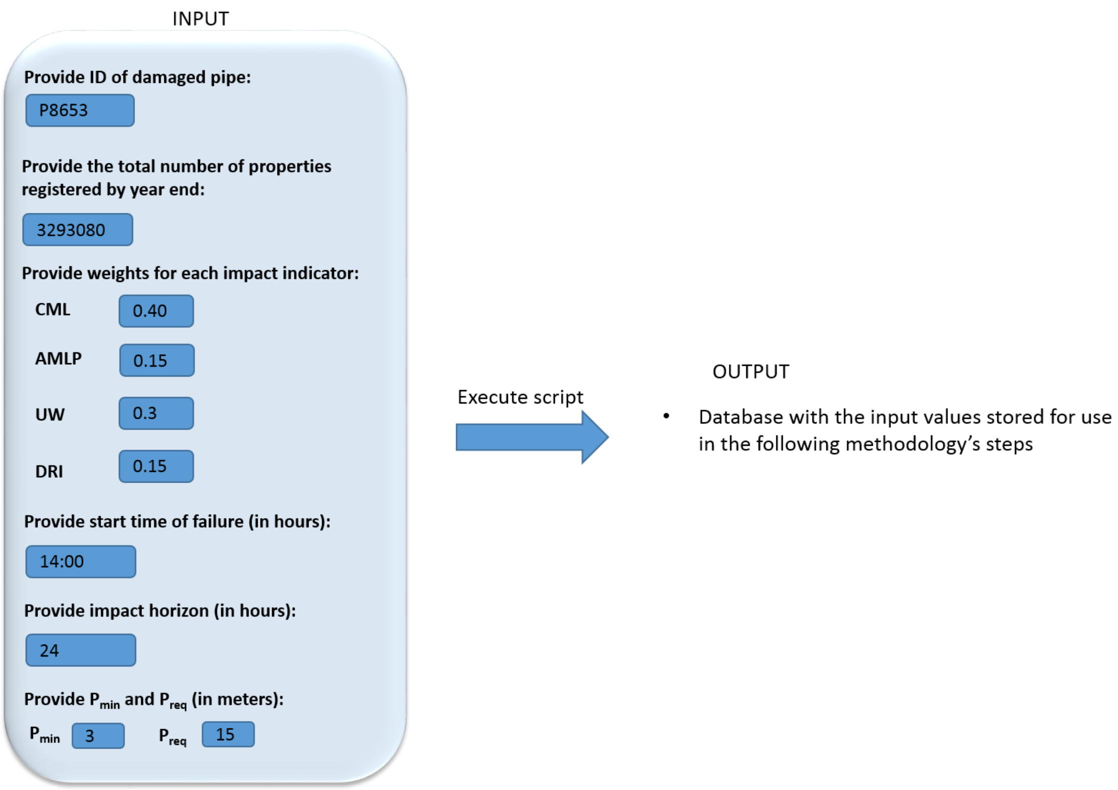

Figure 3-8: Initial general information inputted in the IRPT

In step 1 operators are able to apply the initial impact assessment via the IRPT. For the execution of the initial impact assessment (i.e. 'No intervention' case), no more input information (i.e. in stage 1) is required into the IRPT. This is because all the required information has already passed in the IRPT in step 0. Here the EPANET file with the event simulated is called through the MATLAB environment. The output of this script (i.e. stage 3) is the list of impact indicators and the total end-impact value. Furthermore, in stage 3 of step 1 (i.e. visualisation) the impact indicators can be visualised on a map like in Figure 3-9. It can be observed that apart from the impact indicators, operators can also visualise the pressure timeline of a selected DMA (by inputting the Critical Metered Point, CMP, of this DMA into the tool). In Figure 3-9, the Supply Interruption (SI) duration (used in the calculation of the CML impact indicator) is visualised as an example. CML cannot be visualised on a map because it is a single impact value. In the same way as in Figure 3-9, the UW and the low pressure duration (for the AMLP indicator) can be visualised. The DRI is visualised by colouring the pipes in the same way the nodes are coloured in Figure 3-9. The negative pressures of the order of -0.5 appearing in Figure 3-9 are normal even during the pressure-driven analysis in EPANET due to isolation of a big part of the network model.

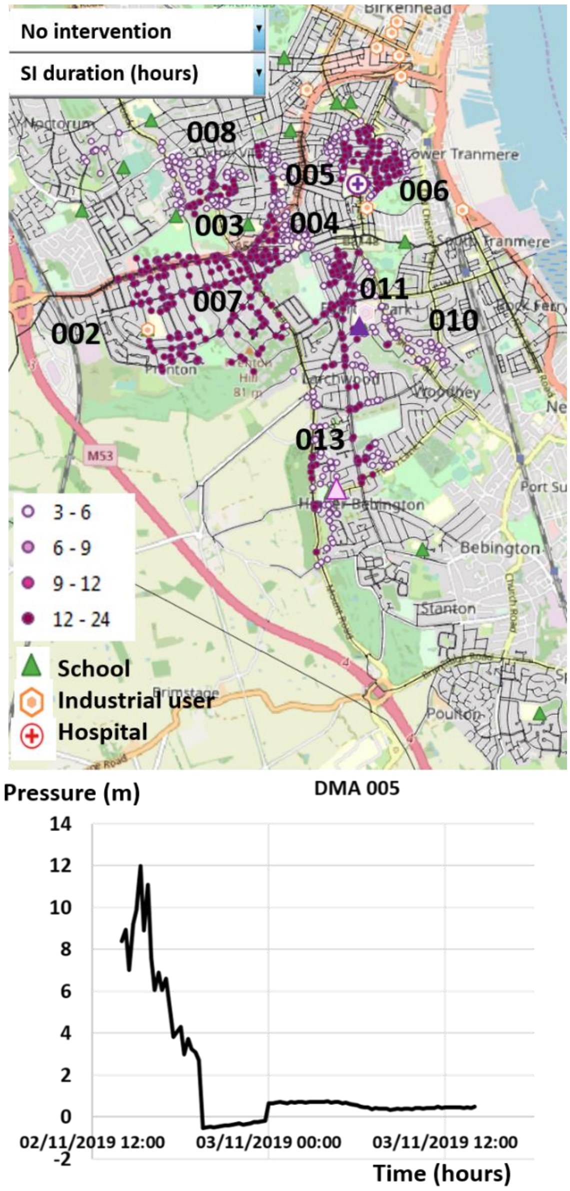

Figure 3-9: Visualisation on a QGIS map (i.e. stage 3) of the SI duration for the initial impact assessment (i.e. methodological step 1)

In step 2 operators are able to identify the best isolation plan via the IRPT. Step 2 includes three independent pieces of script. In the first one, operators input no more additional information in the IRPT in stage 1 and the IRPT proposes the set of the closest valves (as shown in Figure 3-10a) based on graph theory. If operators find that at least one of these valves does not operate or is inaccessible, then they input (the list of) these/this valve(s) into the IRPT (in the second script of this step), as shown in Figure 3-10b. Then the IRPT proposes the next closest valves (i.e. alternative plan) based on graph theory. The output of the above scripts is the list of the best (i.e. closest to the event and operable) isolation valves. As soon as the best isolation plan is identified, then an impact assessment (the third script of this step) is carried out. For this one, a separate script is run by inputting in the IRPT the identified set of isolation valves and a desired isolation start time (as shown in Figure 3-10c). The output of this script is the list of impact indicators and the total end-impact value of the selected isolation plan, as well as the impact indicators visualised on a map (as shown in Figure 3-9).

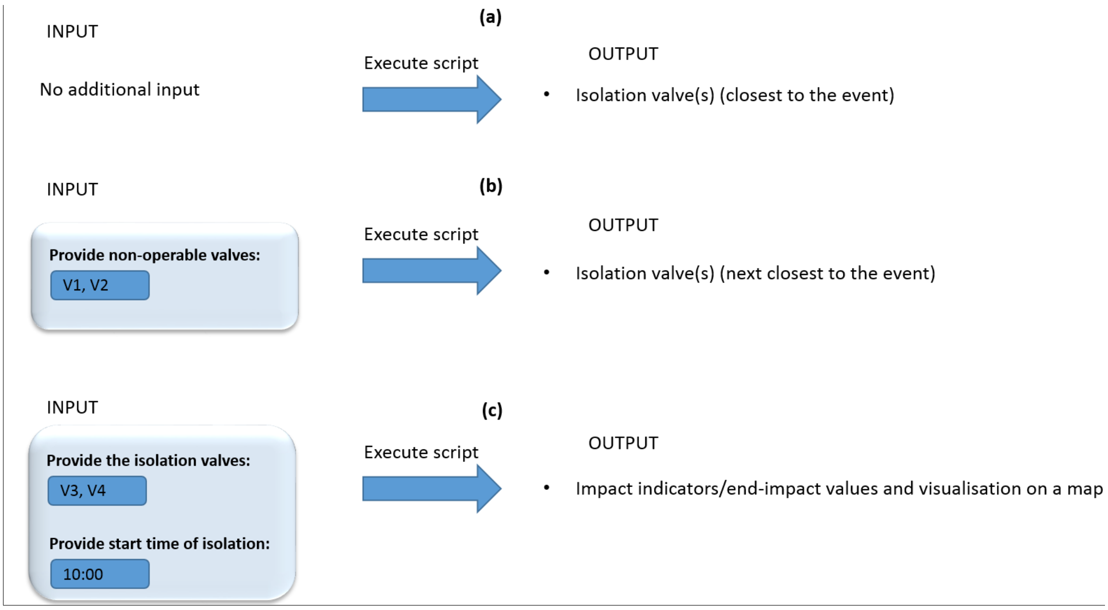

Figure 3-10: (a) Input information into the IRPT for the isolation plan identification (i.e. step 2 of the response methodology) (b) Input information into the IRPT for the identification of alternative isolation plan (c) Input information into the IRPT for the estimation of end-impact of a selected isolation plan

In step 3 operators can generate a manual solution within the IRPT. For the execution of step 3, two additional pieces of information are required to be inputted into the IRPT (i.e. in stage 1), as shown in Figure 3-11. The output of this script (i.e. stage 3) is the list of impact indicators and the total end-impact and cost values for the provided manual response. Furthermore, in stage 3 of step 3 (i.e. visualisation) the impact indicators can be visualised on a map like in Figure 3-9 (i.e. in the same way as in the 'No intervention' case).

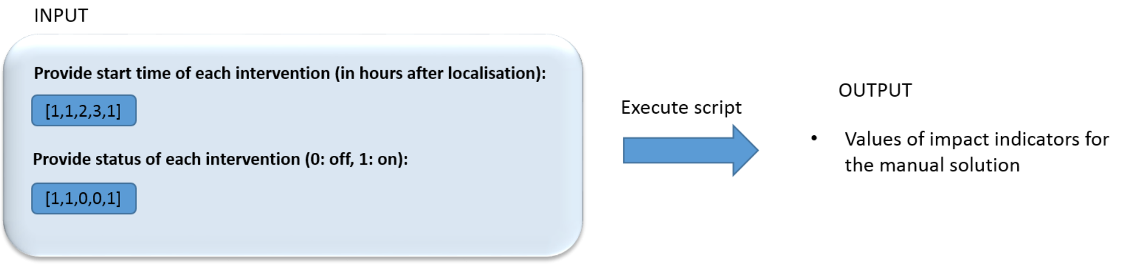

Figure 3-11: Input information into the IRPT for the generation of manual solution (i.e. step 3 of the response methodology)

In step 4 operators are able to identify near-optimal solutions via the IRPT. Step 4 includes three independent pieces of script (based on the optimisation strategy described in sub-section 3.3.3). In the first one (i.e. based on step 1a of the optimisation method), operators input no more additional information in the IRPT in stage 1. Then the IRPT identifies the affected nodes/DMAs and the intervention options located in the affected and unaffected DMAs (as shown in Figure 3-12a). In the second piece of code (i.e. based on step 1b of the optimisation method), they input the list of the identified interventions from step 1a and a desired start time of all interventions, in stage 1. Then the IRPT calculates and presents to the operators the end-impact and cost values for every individual evaluation of the above single interventions (in stage 3), as shown in Figure 3-12b. Finally, a separate script is run for step 2 of the optimisation method (i.e. heuristic algorithm). Here, operators input in the IRPT the *x* number of interventions (i.e. their end-impact and cost as identified in step 1c of the optimisation method). Then IRPT runs the heuristic algorithm and identifies the Pareto front of near optimal solutions. This Pareto front is then presented to them in stage 3 (as shown in Figure 3-12c). In stage 3, a near optimal solution on the Pareto front can be selected by operators and its end-impact can be visualised on a map (as shown in Figure 3-9).

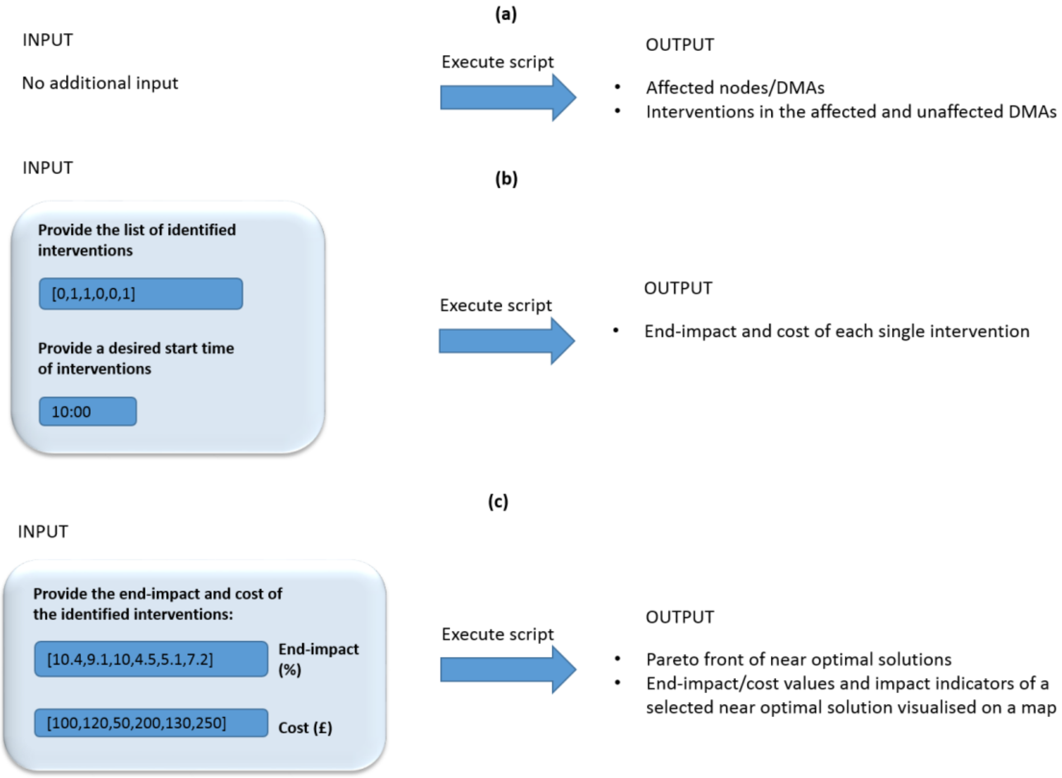

Figure 3-12: (a) Input information into the IRPT for the identification of affected nodes/DMAs and interventions in the affected DMAs (i.e. step 1a of the optimisation method) (b) Input information into the IRPT for the calculation/presentation of end-impact and cost of the identified interventions from step 1a (i.e. step 1b of the optimisation method) (c) Input information into the IRPT for the identification of the Pareto front of near optimal solutions (i.e. step 2 of the optimisation method)

In step 5 operators can manually modify an identified solution (from the previous steps) via the IRPT. The identified solution might be result of a manual suggestion (in step 3) or of optimisation (in step 4). Operators in this step can modify the status and the start time of each intervention of the identified solution. For the execution of step 5, two additional pieces of information are required to be inputted into the IRPT (in stage 1), the same as in step 3 (see Figure 3-11). The output of this script (i.e. stage 3) is the list of impact indicators and the total end-impact and cost values for the provided manual response. Furthermore, in stage 3 of step 5 (i.e. visualisation) the impact indicators can be visualised on a map like in Figure 3-9), as well as compared on single-window GIS map (see Figure

3-13). Comparing different solutions in a single window facilitates quick and effective response decision-making. The negative pressures of the order of -0.5 appearing in Figure 3-13(a) are normal even during the pressure-driven analysis in EPANET due to isolation of a big part of the network model.

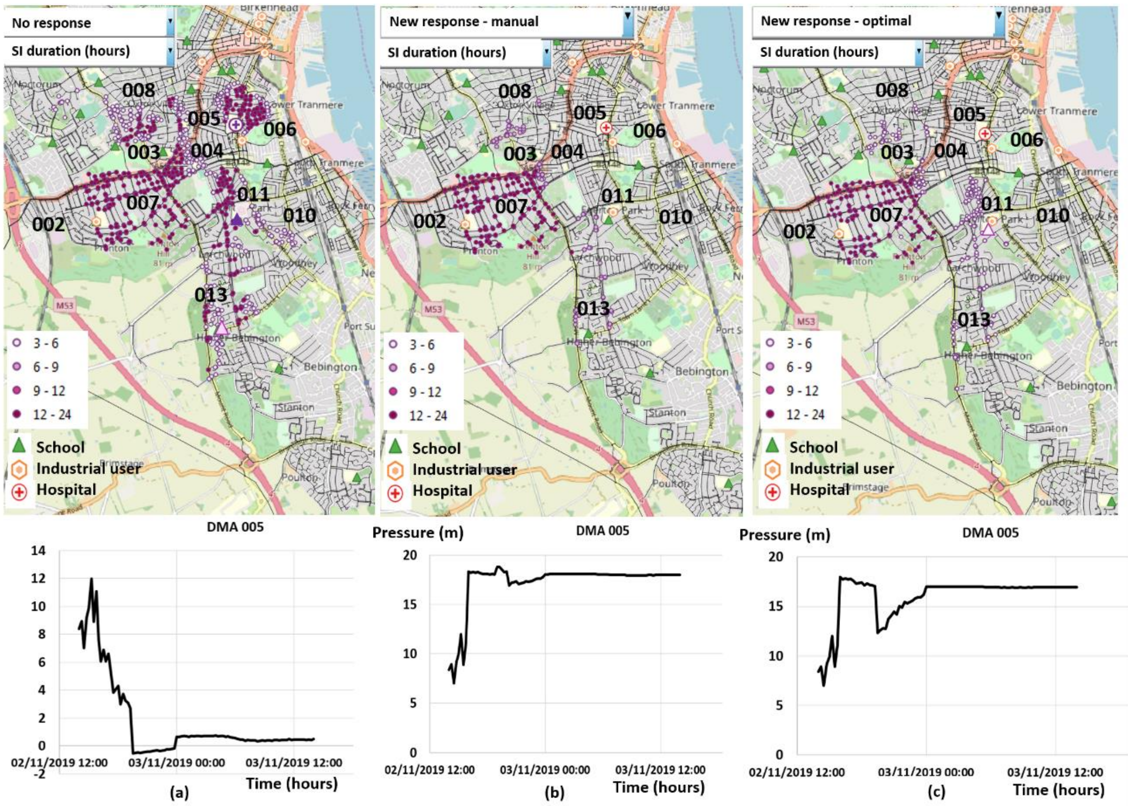

Figure 3-13: Comparison of different solutions, i.e. (a) No intervention case, (b) a modified manual solution and (c) a selected optimal solution, generated within the IRPT in a single window

3.5 Summary

This chapter presented a near real-time response methodology to water network events. Initially the current utility practice was described. Then the proposed response methodology concept, impact assessment, optimisation method and modelling were presented. Finally, the implementation of the response methodology within a decision support tool was shown.

In section 3.3 the response methodology was presented in detail. As it was shown, the key novelties of the response methodology are as follows: i) structured yet flexible approach supporting and guiding the operator throughout the entire response process (from detection and localisation of a failure event to implementation of the identified response solution in the field) is designed whilst allowing the operator to have a final say, (ii) novel interaction with the operator in near real-time via the IRPT (e.g. 'what-if' scenarios) without hydraulic expertise requirements, (iii) provision of automatically generated recommendations (e.g. near optimal response interventions via a novel heuristic algorithm, assessed end-impacts) enabling operators to make better informed decisions, (iv) improved impact assessment (based on realistic impact indicators) that covers different aspects of the event with respective indicators calculated consistently (i.e. via the same impact metrics) for every proposed response intervention (to facilitate easy comparison between different response solutions), and (v) more realistic selection of operational interventions (i.e. considering operational costs, availability of different types of interventions, start time of interventions' implementation, duration of interventions' implementation, etc.).

In section 3.4, the implementation of the response methodology within a decision support tool was presented. The decision support tool, called IRPT, is developed in the MATLAB environment and links to EPANET for the execution of hydraulic simulations and to QGIS for the visualisation of the impact indicators on a map. IRPT consists of six main MATLAB coding-bodies, each one executing a set of MATLAB functions. The first coding-body includes the functions to store in the MATLAB space the initial general information required for all the next steps. The next five steps are the five methodological steps, each one conducted independently and as many times as operator desires. In each of the five methodological steps, there is the first stage where the information is inputted into the tool by the operator (not hydraulic expertise is required). Then in the second stage the hydraulic simulations are conducted by calling the EPANET functions and the end-impact/cost is calculated. Finally in the third stage the impact indicators are visualised on a map.

The proposed response methodology has been applied on a semi-real case study (i.e. a case study based on a real system and event, but with event timeline and operators' responses simplified for modelling and computational reasons). The results obtained (presented in the next chapter) demonstrate the potential of the response methodology and its application through the interactive tool (i.e. the IRPT) to improve water utilities' current practice.

4 VALIDATION OF THE NEW RESPONSE METHODOLOGY

4.1 Introduction

The present chapter aims to illustrate the benefit of interaction of water utility operators with the IRPT in identifying a suitable response solution to a water network event. In the present semi-real case study (i.e. case study based on a real system and event, but with simplified event timeline and operators' responses for modelling and computational reasons), the solution identified after interaction with the IRPT is referred to as the 'New methodology response'. The response solution based on utilities' current practice (hereafter referred to as the 'Current practice response') is also identified in the present chapter. The 'New methodology response' (identified in near real-time, i.e. approximately 1 hour after event detection/localisation) is ultimately compared with the 'Current practice response', in order to demonstrate the benefit resulting from the operator's interaction with the IRPT.

The chapter is organised as follows. In section 4.2, the semi-real case study is described. In section 4.3, the IRPT's steps are implemented for the case study's event in order to identify the 'New methodology response'. Specifically, initially step 1 of the methodology is used to perform the initial impact assessment, then step 3 is used to identify and assess a manually proposed solution (using the 'what-if' scenario simulation capability afforded by the IRPT). Then, step 4 is used to calculate the optimal solutions. Finally, step 5 is used to compare the manual solution with the optimal solutions and decide the best/final one (i.e. the 'New methodology response'). The solution selected by operators using the IRPT is ultimately compared with the 'Current practice response' in section 4.4 in order to demonstrate the benefit resulting from the operator's interaction with the IRPT.

4.2 Description of the semi-real case study

The semi-real case study used here is based on the following real system (hereunder called P-Town) and event. On Saturday 2nd November 2019 at 14:00, a WTW that serves approximately 100000 customers located in the North West of England shut down following observation of high turbidity levels. This event was due to a burst on a main within the WTW. The shutdown resulted in intermittent supply and low pressure to some customers. The WTW remained shut until the quality of the water leaving the WTW could be assured to meet the required standards. The utility mobilised ASVs to the area and implemented network changes (i.e. rezoning) in order to minimize customer end-impact. Bottled water was delivered directly to priority services and sensitive customers. The repair was completed 24 hours after the shutdown.

In the IRPT, the shutdown is modelled by closing the pipe downstream the service reservoir (i.e. P8703) directly fed by the WTW (the WTW feeds this service reservoir only) at 14:00, in order to facilitate the hydraulic simulations. As far as the actual utility’s response actions are concerned, a number of simplifications and assumptions were made to simplify the coding required in the IRPT. Hence, ASV injection at each point is carried out by using a single artificial ASV (equivalent to 3 x 30 m^3 ASVs usually sent to site) (see sub-section 3.3.4).

In reality ASVs supplied water intermittently at some injection points (i.e. started at different times during the event and did not inject water consecutively) and with more than three ASVs (i.e. injection loads) used in some cases. Additionally, the rezoning valves considered in the IRPT’s simulations do not necessarily coincide with the rezoning valves actually used by the utility during the event. This is due to the fact that the hydraulic model used did not precisely reflect the real valves layout. Finally, the actual start times of the interventions have been rounded to the next hour (e.g. if an intervention started at 19:30 in real-life, then in the IRPT it assumed to start at 20:00).

Figure 4-1a shows the location of the considered service reservoir and the downstream pipe that was closed (i.e. pipe P8703) for modelling the shutdown, as well as the location of the industrial users, schools, hospital and the network model’s DMAs (each DMA represented with different colouration).

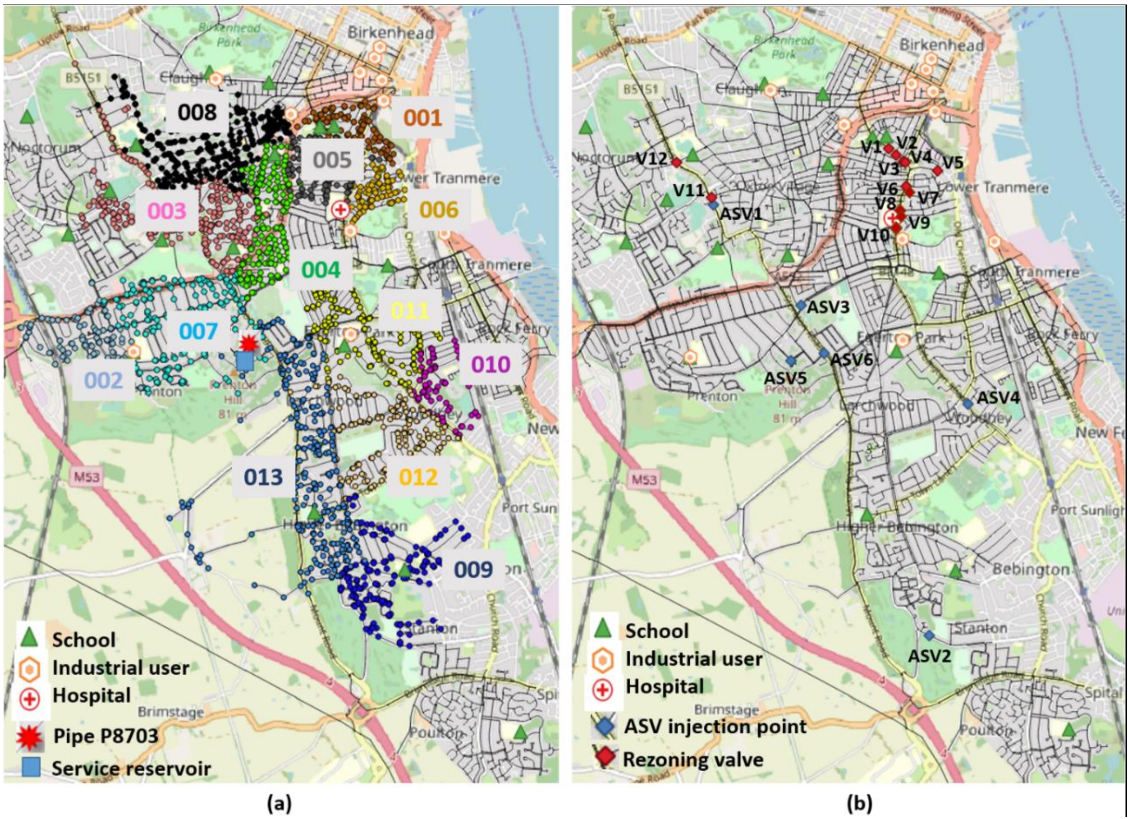

Figure 4-1: (a) Location of the considered service reservoir (fed by the WTW), simulated closed pipe P8703, schools, industrial users, hospital and DMAs; and (b) Location of the available interventions (i.e. rezoning valves and ASV injection points)

Because of all of the above, we refer to the case study under scrutiny as “semi-real”, i.e. based on a real system and event, but with several simplifications and assumptions. Bearing in mind the typical response strategy described earlier, we refer to the response actions shown in Table 4-1 as the ‘Current practice response’, although they only approximate (i.e. in terms of total end-impact, start time of impact, affected areas, etc.) the actual real-life response. This said, it is also important to stress here that many factors may have influenced the actual response actions taken by the utility. These factors have not been accounted for in this study and, hence, the term ‘Current practice response’ should be construed accordingly.

Table 4-1: Semi-real case study's event timeline and 'Current practice response' interventions

Saturday Nov 2nd 2019	
14:00	WTW shut down
15:00	ASV injection in DMA 003 (one injection point)
20:00	ASV injection in DMA 009 (one injection point)
21:00	ASV injection in DMA 004 (one injection point)
22:00	ASV injection in DMA 010 (one injection point)
Sunday Nov 3rd 2019	
00:00	Rezoning from DMA 001 to DMA 005 (five rezoning valves)
00:00	Rezoning from DMA 005 to DMA 006 (five rezoning valves)
00:00	Rezoning from DMA 003 to DMA 008 (two rezoning valves)
01:00	ASV injection in DMA 007 (two injection points)
14:00	Repair is completed

4.3 New methodology response

In this section, the identification of the response solution through the IRPT's steps (i.e. 'New methodology response') is presented. It is worth stressing at this point that step 2 of the IRPT methodology is not applied here, because the event is considered to be the shutdown (i.e. not the burst). Hence, in this case, operators do not need to ask the support of the IRPT for the identification of the best isolation start time and of the best isolation valves to close.

4.3.1 Initial general input into the IRPT (step 0)

Before the implementation of the methodological steps, the following general information is inputted into the IRPT in step 0: 1) the damaged pipe ID is "P8703"; 2) the total number of customers registered in the utility is equal to 3293080 (value obtained by the utility); 3) P_{min} is equal to 3m and P_{req} is equal to 15m (as applied in water utilities' practice); 4) the impact assessment horizon (i.e. simulation duration) is equal to 24 hours = 1440mins; 5) the start time of the event is equal to the event localisation, i.e. at 2pm; and 6) the indicators weights are equal to: w_{CML}=0.4, w_{AMLP}=0.15, w_{UW}=0.3 and w_{DRI}=0.15.

Regarding the impact horizon, it is highlighted that the completion time can only roughly be estimated before the actual repair commences. However, 24 hours is considered to be a reasonable period over which the repair of a major burst is likely to be carried out. Regarding the weight factors of the impact indicators, it is stressed that they are decided by operators based on the priority they wish to give to each of them during the optimisation process (i.e. in step 4). Hence, operators here decide to give priority to reducing CML and UW, as in utilities' practice these indicators are usually considered important. Despite its importance, it was chosen not to give higher priority to DRI in the optimisation problem, because minimisation of the second objective (i.e. cost) is expected to substantially reduce the risk of discolouration (due to minimisation of the number of valve manipulations and ASV injections).

4.3.2 Initial impact assessment (methodological step 1)

The first step of the methodology is to apply the initial impact assessment. Here, operators aim at assessing the initial end-impact over the impact horizon (i.e. until the repair is completed). Based on the above input and the network under investigation: 1) the total number of customers in the section of network under scrutiny is equal to 46545; 2) the maximum value of UW is equal to the total volume of water required to supply the whole section of network under normal operation (equal to 175530m^3); and 3) the maximum value of DRI is equal to the total number of pipes in the section of network (equal to 8750 pipes). Hence, the maximum values of the impact indicators are: CML_{max}=20.35mins/cust (based on Equation 1), $AMLP_{max}$=20.35mins/cust (based on Equation 2), UW_{max}=175530m^3 (based on Equation 3) and DRI=8750 pipes (based on Equation 4). The minimum values of all impact indicators are equal to 0. Then, CML is calculated by the IRPT as equal to 4.0mins/cust, AMLP is equal to 3.6mins/cust, UW is equal to 3330m^3 and DRI is equal to 14 pipes (out of the 8950 pipes in this section of network). This results in a total initial end-impact as equal to 11.2%.

The location of the affected customers with supply interruption (SI) for more than 3 hours is shown in Figure 4-5a (with purple-gradient colouration), in sets of 3 hours (i.e. 3-6, 6-9, 9-12, >12 hours). The above impact values (computed over the 24-hour impact horizon) highlight the significance of this event that affected a wide area comprising different DMAs. The affected area also includes 2 schools, 1 industrial node and the hospital (all purple-gradient coloured depending on the SI duration). However, the risk of discolouration (or DRI) could be considered low (i.e. only 14 pipes are at high risk).

Using the IRPT, operators are also able to check the pressure over the impact horizon and, hence, get a view of when the aforementioned affected customers start getting end-impact. At the bottom of Figure 4-5a, the pressure graph for DMA 005 (selected as an example here because the hospital is located in that DMA) is presented. It can be noticed that DMA 005 (and, hence, the hospital too) starts being affected approximately 5 hours after the shutdown, if nothing is done. The IRPT also provides the capability to visualise the other aspects of the impact, such as the low pressure duration at each node, the volume of undelivered water at each node and the discolouration risk increase at each pipe, as well as for different DMAs, in a similar way as shown in Figure 4-5a. All this is a significant advantage over what done/available as part of current practices. Step 1 is completed in 3 minutes, i.e. as long as it takes of a single impact/cost evaluation to take place (for the complex network of P-Town).

4.3.3 Manually proposed solution (methodological step 3)

For the purposes of this work, a fictional operator proposes a realistic (i.e. that could have potentially be identified in the utility's control room) manual solution (denoted hereafter as 'New response - manual') in step 3 of the methodology, after having carried out the initial end-impact assessment. The available interventions (i.e. 12 rezoning valves and 6 ASVs) are shown in Figure 4-1b. Looking at the initial end-impact (in Figure 4-5a), the fictional operator decides to inject water into the affected DMAs 003, 004, 010 and 007 (i.e. by using all available ASVs) and rezone affected DMAs 005, 006 and 008 by opening all the available rezoning valves. This is because the fictional operator wants to intervene into all affected DMAs where available interventions exist. Then, looking at the pressure graphs of the DMAs where ASV injection is available (i.e. DMAs 003, 004, 010 and 007), presented in Figure 4-2 for the ‘No response’ scenario, he/she decides to start injecting into these DMAs 5 hours after the shutdown (i.e. when the impact starts in the horizon). This is because he/she wants to allow plenty of time to mobilise the ASVs and also allow injection to start at 19:00 when a peak in demand is expected. He/she finally decides to rezone as soon as possible (here assuming 2 hours after the shutdown to allow plenty of time for technicians to get to site), because rezoning for longer period is expected to significantly reduce end-impact without increasing cost (i.e. rezoning duration does not affect cost, see cost function in the section of impact assessment in the chapter of response methodology). Bearing in mind the above, it is worth stressing that the IRPT supports operators with modelling different ‘what-if’ scenarios in an easy way. For example, the same fictional operator could have also tried opening less valves to rezone those DMAs just by modifying the information he/she did input in one field of the IRPT’s graphical user interface.

Assuming that c_{rez} is equal to £27, c_{ASV} is equal to £32 (both provided by the utility to make this manual solution more realistic) and d_{rez}=2 hours (i.e. one hour for technicians to open one rezoning valve and another one hour to close it), then CML is equal to 1.2mins/cust, AMLP equal to 1.7mins/cust, UW equal to 1235m^3 and DRI is equal to 316 pipes in the network. The total end-impact is equal to 4.5% and the cost is equal to £813. The location of the affected customers with SI of more than 3 hours and the pressure graph of DMA 005 after applying the ‘New response - manual’ solution are shown in Figure 4-5b. Step 3 is completed in 3 minutes, i.e. as long as it takes for a single evaluation of one manual solution to be conducted.

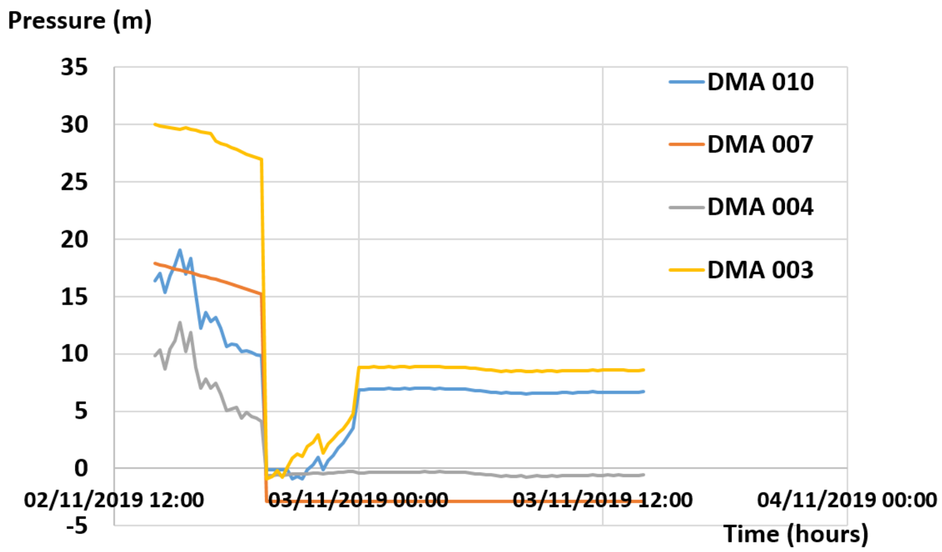

Figure 4-2: Pressure vs time of different DMAs for the ‘No response’ case

4.3.4 Optimal solution (methodological step 4)

After having assessed the end-impact/cost of their manually proposed solution in step 3, the fictional operator asks the support of the optimisation in step 4. As mentioned earlier, operators here decide to give priority to reducing CML and UW. It is stressed that the weight factors selected here are indicative to illustrate the desired priority, but can be easily changed in the IRPT by the decision-maker.

In the context of this step, the optimisation process is followed step by step. Hence, in offline step 0 of the optimisation method, all the available interventions are identified by the operators. It is stressed that step 0 is not conducted in real-time. Hence it is assumed that this step has already taken place before the confirmation of the present event. For the network under scrutiny, 18 available interventions are identified, i.e. 6 ASVs and 12 rezoning valves. The location of the available interventions is shown in Figure 4-1b. It can be noticed that ASV1 is located in DMA 003, ASV2 in DMA 009, ASV3 in DMA 004, ASV4 in DMA 010, ASV5 and ASV6 in DMA 007. Rezoning valves V1-V5 link DMA 001 with DMA 005, V6-V10 link DMA 005 with 006 and V11, V12 link DMA 003 with DMA 008. It is stressed that the main point of Figure 4-1b is to show the DMAs where the interventions are located. This is required when applying the step 1 of the optimisation method (see following paragraph) where the interventions that link affected with unaffected DMAs are only nominated. Hence it is only important for the interventions IDs and their approximate location to be clear in the figure.

In online step 1 and step 1a, the 18 available interventions are narrowed down as follows. The rezoning valves that link affected with unaffected DMAs and the ASVs located in affected DMAs are only nominated to the next step. It is stressed that the affected DMAs are found based on the initial system condition, i.e. the ‘No intervention’ case, where the system with the closed pipe is modelled (i.e. modelling the shutdown). The affected DMAs (i.e. 002, 003, 004, 005, 006, 007, 008, 010, 011 and 013) are presented in Figure 4-3. Hence, the following interventions are nominated: V1-V5 (linking unaffected DMA 001 with affected DMA 005), ASV1 (in DMA 003), ASV3 (in DMA 004), ASV4 (in DMA 010), ASV5 (in DMA 007) and ASV6 (in DMA 007). It is noticed that in total 10 interventions (i.e. 5 rezoning valves and 5 ASVs) are considered as potential decision variables for the next step. Step 1a takes approximately 3mins to be completed (i.e. time required to run a single evaluation of the system for the ‘do nothing’ case).

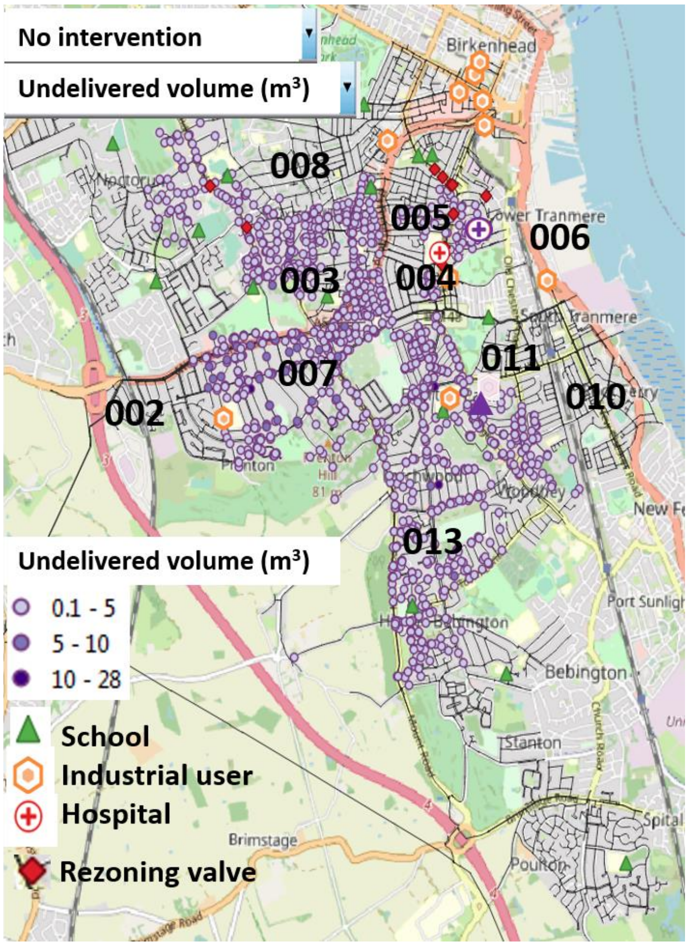

Figure 4-3: Location of affected nodes/DMAs for the ‘No intervention’ case in P-Town network

In online step 1b, the above 10 interventions are assessed individually for a fixed start time. Here, the start time 4pm is selected (i.e. 2 hours after the event detection) and put in the IRPT together with the identified interventions from step 1a. Operators are quite likely to select this start time assuming that it will take approximately 1 hour for them to identify the intervention plan and another 1 hour for technicians to get to the field and implement the interventions. The assumption of 1 hour for the duration of the intervention plan identification lies on the fact that a single evaluation takes approximately 3 minutes to take place for the complex P-Town network. Hence, step 1b takes approximately 10 (evaluations) x 3 (mins/evaluation) = 30mins. Then, step 2 (i.e. optimisation through heuristic) will also take approximately another 30mins, because in the heuristic 10 combinations of interventions will be assessed (i.e. equal to the number of nominated interventions/decision variables). The time to complete the rest of the sub-steps (i.e. step 1a and 1.3) is negligible. The end-impact and cost of the 10 identified interventions for the start time 4pm are shown in Table 4-2. It can be observed that all the 10 identified single interventions reduce the end-impact of the 'No intervention' case (i.e. equal to 11.2%). Hence, all of them are nominated as decision variables to the subsequent step of optimisation.

In the online step 1c all of the identified single interventions are selected, because 10 combinations of interventions for the P-Town network can be assessed in approximately 30mins and hence in near-real time after the event detection/localisation.

Table 4-2: End-impact and cost (£) of single interventions for the P-Town event

Intervention type		**Start time**	
		2pm	**4pm**
No intervention	End-impact	0.1120	-
	Cost	0	-
ASV1	End-impact	-	0.1071
	Cost	-	120.9
ASV3	End-impact	-	0.1100
	Cost	-	24.18
ASV4	End-impact	-	0.1109
	Cost	-	64.48
ASV5	End-impact	-	0.1100
	Cost	-	16.12
ASV6	End-impact	-	0.1103
	Cost	-	16.12
V1	End-impact	-	0.0704
	Cost	-	55.02
V2	End-impact	-	0.0752
	Cost	-	55.02
V3	End-impact	-	0.0735
	Cost	-	55.02
V4	End-impact	-	0.0497
	Cost	-	55.02
V5	End-impact	-	0.0845
	Cost	-	55.02

In step 2 of the optimisation method the heuristic algorithm is applied. Here operators input in the IRPT the end-impact and cost of the identified decision variables (i.e. 10 interventions). In step 2a of the heuristic, the initial solution is identified by the algorithm as the single intervention with the lowest cost. In Table 4-2 it can be observed that ASV5 and ASV6 obtain the lowest cost equal to £16.12. From these two single interventions, ASV5 is selected as the initial solution, because the end-impact is lower/better (i.e. 11.00%) than the end-impact of ASV6 (i.e. 11.03%).

Then, in step 2b of the heuristic algorithm, the subsequent solution is identified as the single solution with the lowest end-impact among all interventions. In this example, the solution with the lowest end-impact is equal to 4.97% obtained by V4 (Solution 2). This solution reduces the end-impact (i.e. at least one of the two objectives) of Solution 1 and hence it is accepted. In the subsequent solution (i.e. Solution 3) the single intervention with the next lowest end-impact is added to Solution 2 (i.e. the last accepted solution). As noticed in Table 4-2, V1 obtains the next lowest end-impact (equal to 7.04%) and is added to Solution 2. Hence, Solution 3 is the combination of V4 and V1. Table 4-3 shows the end-impact and cost of all the solutions (i.e. intervention combinations) identified by the heuristic. It is observed that Solution 3 with end-impact equal to 5.00% and cost £110.04 does not further reduce end-impact or cost comparing to Solution 2 and hence it is rejected. Because Solution 3 is rejected, in subsequent Solution 4, V1 is not considered and the single intervention with the next lowest end-impact is added. In Table 4-2 it is observed that V3 obtains the next lowest end-impact and is combined with V4 in Solution 4. Now, Solution 4 does further reduce end-impact comparing to Solution 2, and hence it is accepted, as shown in Table 4-3. The same process is followed until all the single interventions have been added (i.e. after 10 evaluations, as shown in Table 4-3).

Table 4-3: Solutions identified by the heuristic algorithm for the P-Town event compared to the 'No intervention' case

Solutions/Iterations	**End-impact (%)**	**Cost (£)**	
No intervention	11.2	0	
Solution 1 (ASV5, t=4pm)	**11.0**	**16.12**	**accept**
Solution 2 (V4, t=4pm)	**4.97**	**55.02**	**accept**
Solution 3 (V4/V1, t=4pm)	5.00	110.04	reject
Solution 4 (V4/V3, t=4pm)	**4.95**	**110.04**	**accept**
Solution 5 (V4/V3/V2, t=4pm)	4.97	165.06	reject
Solution 6 (V4/V3/V5, t=4pm)	5.11	165.06	reject
Solution 7 (V4/V3/ASV1, t=4pm)	**4.31**	**239.00**	**accept**
Solution 8 (V4/V3/ASV1/ASV5, t=4pm)	**4.26**	**255.12**	**accept**
Solution 9 (V4/V3/ASV1/ASV5/ASV6, t=4pm)	**4.09**	**279.30**	**accept**
Solution 10 (V4/V3/ASV1/ASV5/ASV6/ASV4, t=4pm)	**4.05**	**367.96**	**accept**

The 10 solutions proposed by the heuristic algorithm (shown in Table 4-3) are finally checked for optimality in step 2j online. This implies that each proposed solution should not be better than any other solution (i.e. Pareto front). It is noticed that the accepted solutions in Table 4-3 are already the optimal ones and are the final solutions included in the Pareto front.

In Table 4-3, it is noticed that all solutions (either the accepted or the rejected ones) obtain lower end-impact and higher cost than the 'No intervention' case, as expected. Then, Solution 1 was selected by the algorithm as the single intervention with the lowest cost (based on the algorithm concept described in the Response Methodology chapter). This cheapest solution, also, obtains the highest end-impact comparing to the rest of solutions, placing it at the upper left of the Pareto front (see also following Figure 4-4). Solution 2 was identified by the algorithm as the single intervention with the lowest end-impact from Table 4-2. This makes Solution 2 be placed at the second point in the Pareto front (see also following Figure 4-4), because the subsequent accepted solutions obtain lower end-impact and higher cost than Solution 2. It is also noticed that every subsequent solution (Solutions 3 to 10) either reduces end-impact and/or increases cost, because at every iteration the single intervention with the next lowest end-impact is added. This is expected, because the more single interventions with the next lowest end-impact are added to a response solution, the more likely it is that the end-impact will be reduced and/or the cost will be increased. Finally, in Table 4-3 it is noticed that only the solutions that reduced end-impact were accepted, because the cost at every iteration was either the same or increased.

Finally, as also mentioned earlier, step 2 of the optimisation method takes approximately 30mins (i.e. near real-time). Hence the whole optimisation process took approximately (less than) 1 hour.

In Figure 4-4, the heuristic's Pareto front of near-optimal solutions (i.e. green colour), the 'New response - manual' solution (blue colour) and the 'No response' case (i.e. yellow colour) are presented.

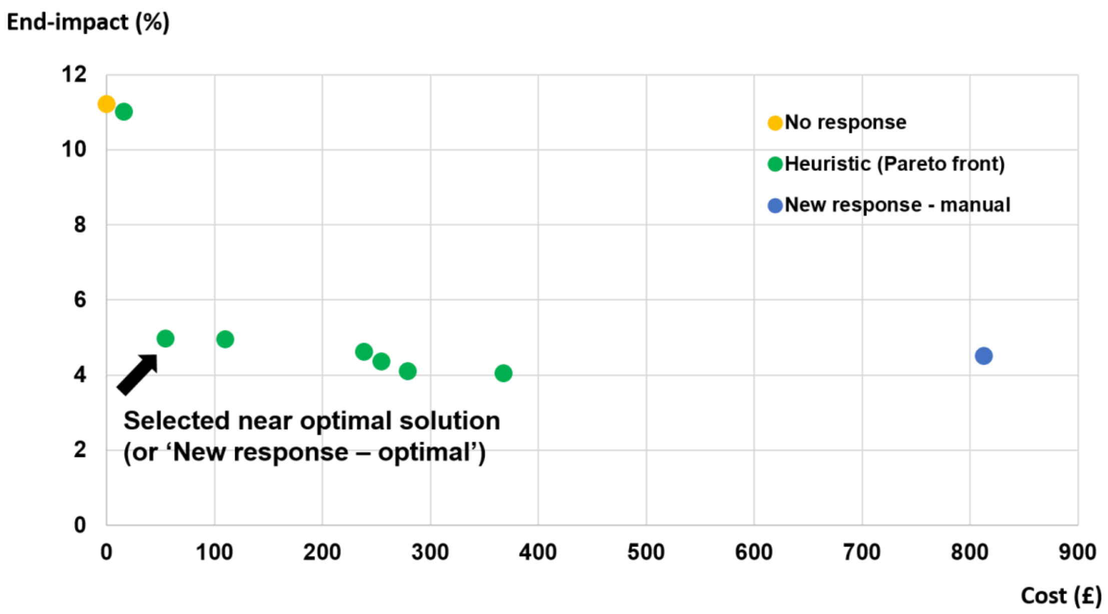

Figure 4-4: End-impact (%) vs cost (£) of near-optimal (heuristic) solutions, the 'New response - manual' and the 'No response'

4.3.5 Identification of the final response plan (methodological step 5)

After the optimisation (step 4 of the methodology) is completed, in step 5 the fictional operator decides to compare the identified optimal solutions with the ‘New response - manual’ solution in order to identify the best response plan. Here, for illustration reasons, he/she selects one solution from the Pareto front in order to compare it with the ‘New response - manual’ solution. The selected optimal solution (denoted hereafter as ‘New response - optimal’, pointed with a black arrow in Figure 4-4) is a solution with significantly reduced end-impact for a small cost increase compared to the rest of the optimal solutions with less cost and bigger impact (i.e. solutions found at the left side of the selected one) on the Pareto front. Such solution is quite likely to be selected by a decision-maker.

The values of the impact indicators of the ‘New response - optimal’ solution (as well as those of the ‘New response - manual’ and ‘No response’) are shown in Table 4-4. As it can be seen from this table, the values of CML and UW are significantly reduced in the ‘New response - optimal’ compared to the ‘No response’ case. This implies that the considered weight factors were effective in this problem. It is also observed that the ‘New response - manual’ solution obtains smaller end-impact values for the CML, AMLP and UW compared to the ‘New response - optimal’ solution. However, cost and DRI are significantly reduced in the ‘New response - optimal’ solution compared to the ‘New response - manual’ solution due to the optimisation enforcing cost minimisation (i.e. two-objective optimisation problem). As expected, minimisation of cost function has also reduced the number of rezoning valves to open and the injection time, resulting in reduced disturbance in pipe flows, and consequently reduced risk of discolouration increase (i.e. low DRI value).

The ‘New response - optimal’ solution also suggests only one intervention, i.e. opening one rezoning valve V4 which feeds DMA 005, starting at 4pm (i.e. 2 hours after shutdown). No injection from ASVs is suggested, which explains the minimised cost (i.e. £55) of this solution. The significantly reduced total end-impact of the ‘New response - optimal’ solution (i.e. 4.97%), compared to the 11.2% of ‘No response’, is a consequence of starting the rezoning very early in the simulation (although only one valve is opened). It is also observed that the total end-impact of the ‘New response - manual’ solution (i.e. 4.5%) is not significantly lower than the total end-impact of the ‘New response - optimal’ solution (i.e. 4.97%). However, the cost of the ‘New response - optimal’ solution (i.e. £55) is much lower than the cost of the ‘New response - manual’ solution (i.e. £813).

Furthermore, Figure 4-5c shows that in the ‘New response - optimal’ solution the number of affected customers with SI has been reduced when compared to the ‘No response’. However, in the ‘New response - manual’ solution the affected area is smaller than the affected area in the ‘New response - optimal’ solution (e.g. DMA 011 is not affected with CML when applying the ‘New response - manual’ solution, but there is CML impact when applying the ‘New response - optimal’ solution). In both solutions the hospital is not affected anymore (see also the pressure graphs in Figure 4-5b and 5c) when compared to the ‘No response’ case. If applying the ‘New response - manual’ solution, the initially (i.e. ‘No response’) affected schools (in DMAs 011 and 013) and the industrial node (in DMA 011) are not affected anymore. However, in the ‘New response - optimal’ solution the school in DMA 011 is still affected, although for less hours (i.e. between 3 and 6 hours) compared to the ‘No response’ case. Through Figure 4-5b and 5c operators are also informed that DMA 007 has still high SI impact (i.e. almost the whole DMA is affected with SI >12 hours, although the total CML is low) in both ‘New response - manual’ and ‘New response - optimal’ solutions. It is reminded at this point that the only available intervention in DMA 007 is injection from 2 ASV points (see Figure 4-1b). Hence, the IRPT also serves the purpose of informing the operators that they should look into more available ASV points and/or available rezoning (e.g. from adjacent unaffected DMA 002) in DMA 007.

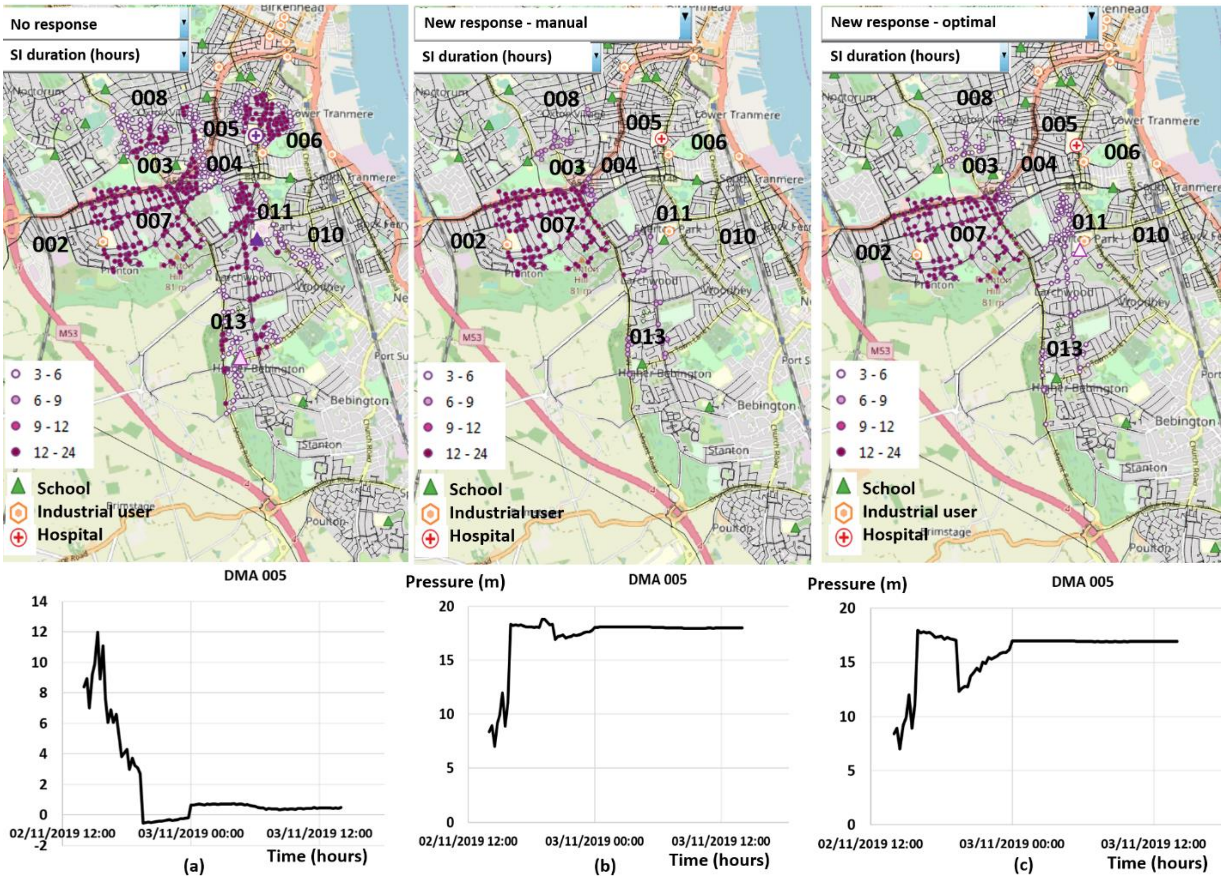

Figure 4-5: Customers affected with SI and pressure graph for the
(a) ‘No response’; (b) ‘New response - manual’ and (c) ‘New response - optimal’

At this point in time (i.e. in step 5 of methodology), based on the information obtained by using the IRPT, the fictional operator has to make the following decision: 1) apply the ‘New response - manual’ solution due to the reduced CML, AMLP and UW when compared to the ‘No response’, 2) apply the ‘New response - optimal’ solution where CML, AMLP and UW are also reduced when compared to the ‘No response’ (although higher than those in the ‘New response - manual’ solution) but with cost and DRI impact much lower than the cost and DRI impact of the ‘New response - manual’ solution, 3) test/assess a different manual solution (i.e. ‘what-if’ scenario) and compare it with the other identified solutions, or 4) select a different near-optimal solution from the Pareto front in Figure 4-4 and compare it with the other identified solutions. For the purpose of this work, the different ‘what-if’ scenarios and the different near-optimal solutions are discounted due to space limitation. Hence, based on the results obtained, it is assumed that the fictional operator is more likely to select the ‘New response -

optimal' solution because of the minimum DRI (and small cost), as well as relatively low values of all the other impact indicators. The 'New response - optimal' solution is therefore considered to be the 'New methodology response' in the remainder of this paper. Step 5 could be conducted in a number minutes, as it includes the process of the decision-making by operators. Here operators compare one manual solution with one optimal solution and hence step 5 is assumed to take approximately 5 minutes to be completed. From the above it is noticed that the whole response decision-making process (i.e. the execution of the 5 methodological steps) took approximately (a little more than) 1 hour.

4.4 Comparison between 'Current practice response' and 'New methodology response'

In this section the CML, AMLP, UW, DRI, cost and total end-impact are calculated by the IRPT for the 'Current practice response' and are presented in Table 4-4. It can be noticed that even though CML, AMLP and UW are reduced when compared to the 'No response' scenario, the 'New methodology response' (i.e. the 'New response - optimal' solution) offers further improvements. Indeed, the 'New methodology response' further reduced all impact indicators (especially DRI and cost). The 'New methodology response' also suggested less number of interventions to implement (i.e. opening of only one rezoning valve compared to opening of 12 valves and injecting from 6 points in the 'Current practice response') justifying the significant improvement in DRI and cost. This might be beneficial for utilities in cases where only a limited number of resources is available during the response decision-making.

In the light of the above, it can be concluded that the 'New methodology response' identified through interaction with the IRPT outperforms the 'Current practice response'. Hence, the IRPT proposed in the context of this work could be of significant value in a water utility.

Table 4-4: Total end-impact and cost of 'No response', 'Current practice response', 'New response - manual' and 'New response - optimal' (or 'New methodology response')

	Customer Minutes Lost (mins/cust)	Average Minutes Low Pressure (mins/cust)	Unaccounted for Water (m^3)	Discolouration Risk Increase (-)	Cost (£)	Total end-impact (%)
No response	4	3.6	3330	14	0	11.1
Current practice response	1.9	2.1	1594	275	1031	6.1
New response - manual	1.2	1.7	1235	316	813	4.5
New response – optimal (or New methodology response)	1.5	1.9	1475	92	55	4.97

4.5 Summary

This chapter presented an application of the proposed response methodology on a semi-real case study (i.e. case study based on a real system and event, but with simplified event timeline and operators' responses). Initially, the semi-real case study was described. Then, the IRPT's steps were implemented for the case study's event in order to identify the 'New methodology response'. The solution selected by operators using the IRPT (i.e. 'New methodology response') was ultimately compared with the 'Current practice response' (i.e. response solution identified with the current utility's response practice) in order to demonstrate the benefit resulting from the operator's interaction with the IRPT.

In section 4.2 the semi-real case study was described. The event is a WTW shutdown that serves approximately 100000 customers in the North West of England. The WTW shut down due to high turbidity levels resulting from a burst on a main within the WTW. The repair of the burst lasted for 24 hours leaving significant part of the network with intermittent supply and low pressure. The utility mobilised a number of interventions (i.e. ASVs and rezones) in order to restore supply as long as repair was being conducted. In the IRPT, the shutdown was modelled as closing the pipe downstream the service reservoir immediately fed by the WTW. A number of additional assumptions for simulating the event in the IRPT, such as rezoning valves' location, number of ASVs and loads of injection, rounded start time of interventions' implementation, makes this case-study semi-real.

In section 4.3, the identification of the response solution through the IRPT's steps (i.e. 'New methodology response') is presented. Initially, step 1 of the response methodology is used to perform the initial impact assessment. In this step it was identified that a significant part of the network (i.e. 10 DMAs, including schools, hospitals and industrial users) were affected (with CML) due to the shutdown. Hence, operators decided in step 3 to propose a manual solution (using the 'what-if' scenario simulation capability afforded by the IRPT). Here, based on the map of affected DMAs and the graph showing the beginning of impact in the horizon (an additional capability of IRPT), they were able to propose a set of interventions and corresponding start times of implementation. Although the manual solution was quite satisfying (except the DRI and cost), step 4 of the response methodology was also applied for demonstration reasons. In step 4 they were able to identify near-optimal solutions by following the heuristic-based, optimisation method (proposed in this work) in near real-time. Finally, in step 5 they compared the manual solution with a selected near-optimal solution. Here, they decided that the best/final solution (i.e. the 'New methodology response') is the selected near-optimal solution, due to much lower values of cost and DRI compared to the manual solution.

In section 4.4, the IRPT was used to calculate the end-impact and cost of the solution identified by the utility based on their current practice (i.e. 'Current practice response'). Then comparison between the 'Current practice response' and the 'New methodology response' showed that the IRPT enabled operators identify a response solution with much lower values in all impact indicators, and especially in DRI and cost. The 'New methodology response' (identified through interaction with the IRPT) also suggested less number of interventions to apply on site. This might be beneficial for utilities in cases where only a limited number of resources is available during the response decision-making.

The key findings derived from the implementation of the response methodology on the above real-life case study are the following:

- The new response methodology although structured (through the 5 steps), it is flexible, as it allows operators decide which step to apply and how many times, before the final decision of a response solution. Hence, in this case study operators decided to propose/assess manually a response solution and then to ask from the IRPT to identify a near optimal solution. If they wished, they could have proposed alternative response solution(s) in step 3 and/or compare it/them with an alternative selected near optimal solution in step 5.
- The comparison between the "Current practice response" and the "New methodology response" showed that the "New methodology response" outperformed the 'Current practice response'. It is concluded then that the IRPT enabled operators identify a satisfying response solution (and also better than the one identified in real-life) in near real-time, even in a complex, real-life network, such as that of P-Town.
- The IRPT solution was identified in near real-time, i.e. approximately 1 hour after event detection/localisation for the complex, real-life network of P-Town.

5 VALIDATION OF THE NEW, HEURISTIC-BASED OPTIMISATION METHOD

5.1 Introduction

The present chapter aims to illustrate the reliability (or accuracy) of the new, heuristic-based method for near optimal response to water network failures in near real-time. Due to the limitation introduced by the new method (i.e. a fixed start time of interventions implementation is considered), the reliability of the method is investigated here. For this purpose, the method's solutions are compared with the solutions of a more advanced/accurate, but also time-consuming, method (e.g. here NSGA II). The accuracy of NSGA II has been tested/validated by many researchers in the past on different optimisation problems (e.g. Preis & Ostfeld 2008; Alfonso et al. 2010; Wang et al. 2013). Hence, the NSGA II is conducted here too (for the same optimisation problem but considering the start time of interventions a decision variable too) in order to compare the optimal solutions (generated by the NSGA II) with the near optimal ones (generated by the method).

The reliability of the proposed optimisation method is tested through two case studies: 1) C-Town (for an assumed pipe failure event) and 2) P-Town (for a real-life event). The first case study has been extensively used in the literature to demonstrate different optimisation methods, e.g. in Mahmoud et al. (2018). The second case study is used here in order to test the method on a more complicated real-life network under a real-life event scenario. The real-life event used in the second case is described thoroughly in chapter 4. The heuristic solutions obtained are compared to the corresponding results published in the literature (i.e. in Mahmoud et al. 2018). The aim of this comparison is to point out the benefit of the method compared to more conventional methods published in the literature. A sensitivity analysis is also conducted in order to investigate the sensitivity of the optimisation method to the start time of interventions implementation.

The chapter is organised as follows. In section 5.2, the optimisation method is validated and demonstrated on the C-Town case study, with the sensitivity analysis being presented in sub-section 5.2.1. In section 5.3, the proposed optimisation method is validated on the P-Town case study. In section 5.4, the present chapter is summarised.

5.2 C-Town case study

The assumed failure event considered here is a burst on pipe P307 detected/localised at 1am and isolated at 2am (i.e. 1 hour after detection/localisation). Figure 5-1 shows the C-Town network layout as well as the network elements and burst. It is highlighted that the isolation start time considered here is the same as the one used in Mahmoud et al. (2018) to allow for the comparison between the aforementioned study and the present one. Hence, the initial system condition here (that needs to be restored/recovered via optimised recovery interventions) is the system with the leaked pipe (at 1am) and isolated main (at 2am) (i.e. the same as in Mahmoud et al. 2018). Selecting a later isolation start time could reduce even more the end-impact, as proposed in the response methodology (see section 3.3). However, the selection of the isolation scenario is part of a more effective overall response methodology and hence not the focus/aim of the present chapter.

The impact horizon starts from the detection/localisation time (i.e. 1am) and lasts until the end of isolation duration 25 hours later (i.e. at 2am of the next day), similarly to Mahmoud et al. (2018). Other assumptions made here which are the same as the ones used in the aforementioned work (to facilitate the comparison) are the following: 1) location of hydrant points (shown in Figure 5-1); 2) location of isolation valves (shown in Figure 5-1); 3) diameter, Hazen-Williams roughness coefficient and maximum length of overland bypasses (linking pairs of hydrants) equal to 200mm, 100 and 300m, respectively; 4) P_{req} = 15m (pressure under which low pressure impact is introduced and hence undelivered volume of water); 5) same intervention types, i.e. PRVs setting adjustment and overland bypasses.

(Rezoning valves and water injection are not considered here as intervention types, because there are not real-life data about them for the C-Town network and also they are not used in Mahmoud et al. 2018); 6) PRV settings allowed to change are: no increase, 5% increase, 10% increase, 15% increase, 20% increase, or 25% increase, all relative to the original PRV setting; and 7) assumption of recovery initialisation (i.e. start time of all interventions) at 9am (i.e. 8 hours after event detection/localisation). It is stressed that the same assumption/limitation is used in the heuristic to facilitate the comparison between the two studies. However this is not the case with the NSGA II conducted for the case study in the present project where each intervention is allowed to start at a different time in the horizon.

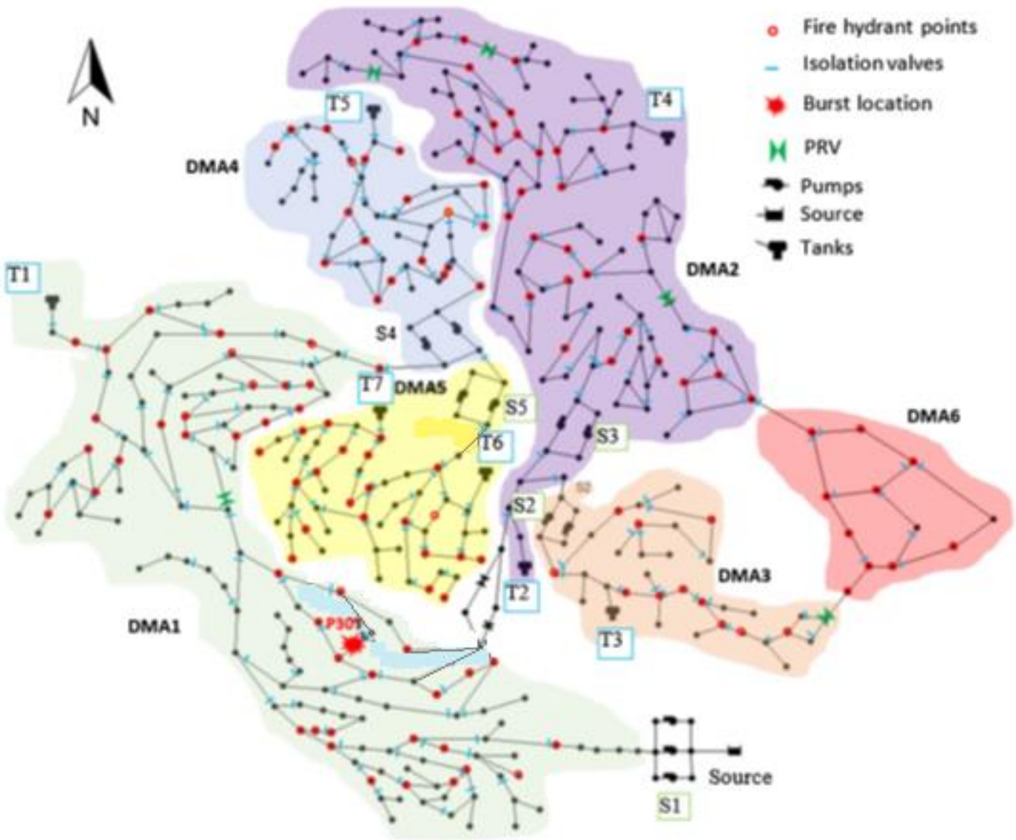

Figure 5-1: C-Town network layout with the simulated event (burst) on pipe P307 (Mahmoud et al. 2018)

One significant discrepancy between the previous work and the present one is the impact assessment. Mahmoud et al. (2018) assess end-impact in a more conventional way, i.e. by considering only the volume of water undelivered to the customers. Here, end-impact is calculated taking into account different impact aspects (see impact assessment method in sub-section 3.3.2), including supply interruption (CML index), low pressure (AMLP index), undelivered water (UW index) and discolouration risk increase (DRI index). The same weight factors for all impact indicators have been used (see Eq. 5).

Additionally, the second optimisation objective differs between the two studies. Mahmoud et al. (2018) optimises for the number of interventions (i.e. again in a more conventional way), whereas here the cost of the recovery interventions is used. It is stressed that smaller number of interventions does not always imply lower cost due to particular hydraulic network requirements (e.g. use of only one ASV injection point might be quite expensive when injecting many hours to meet the required demand).

One additional discrepancy is that the opening/closing of isolation valves is not considered here as possible intervention type, as done in the previous work. This is due to the fact that manipulation of isolation valves is not a common means to intervene into the network when a failure occurs. It is stressed here that the opening/closing of isolation valves is not considered as intervention type during the identification of response solutions, i.e. in steps 3, 4 and 5 of the proposed response methodology. Isolation however is separately conducted in step 2 of the response methodology.

Finally, Mahmoud et al. (2018) make use of the NSGA II method to solve their optimisation problem, whereas here the optimal solutions are identified based on the heuristic-based method. Although the above discrepancies, it is assumed here that it is still worth comparing the results between the two studies. In that way, the difference in optimal solutions will be demonstrated when different aspects of impact, selection of interventions (number of interventions vs cost) and optimisation methods are considered.

Hereunder the proposed optimisation method is implemented step by step (see sub-section 3.3.3) for the C-Town case study. In the offline step 0, all the intervention types (i.e. overland bypasses and PRVs) and possible locations are identified for the C-Town network. The initial list of interventions includes 352 overland bypasses and 5 PRVs for the C-Town network model. In the online step

1a, the initial list is narrowed down by identifying: (a) the overland bypasses that link affected with unaffected DMAs, (b) the overland bypasses located in the affected DMAs, and (c) the PRVs upstream affected nodes. Hence, 247 overland bypasses are nominated to the online step 1b, out of which: 35 overland bypasses link (affected) DMA1 with (unaffected) DMA5, 20 bypasses link (affected) DMA2 with (unaffected) DMA4 and 192 overland bypasses are located in the affected DMA1 and DMA2. No PRV was identified to be upstream affected nodes, hence no PRV is nominated to the next step. Figure 5-2 shows the affected nodes/DMAs for the 'No intervention' case, the PRVs and some overland bypasses (i.e. the ones used in the intervention plans proposed by the optimisation as shown later, for clarity reasons).

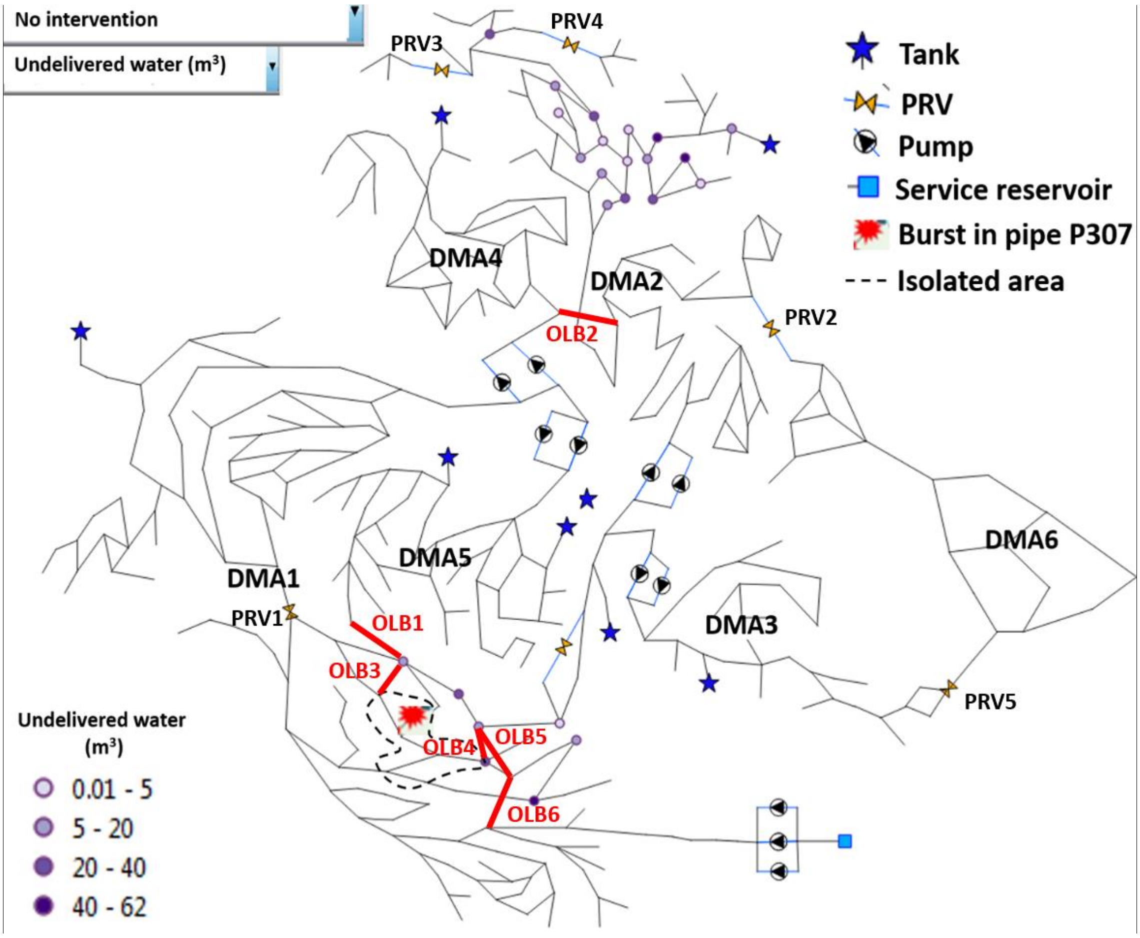

Figure 5-2: Location of affected nodes for the 'No intervention' case (i.e. with burst on pipe P307 and isolation in place), isolated area, PRVs and overland bypasses OLB1, OLB2, OLB3, OLB4, OLB5 and OLB6 in the C-Town network

In the online step 1b (i.e. individual evaluation step), the 247 bypasses are assessed individually (for their total aggregated end-impact and cost) for a fixed start time in the impact horizon. Here it is assumed that operators decide the interventions start at 9am (i.e. 8 hours after detection), i.e. similarly to Mahmoud et al. (2018). This start time is a realistic decision, as it assumes that interventions start when there is peak in demand, as well as it allows plenty of time for the technicians to reach the site and start implementation. In the online step 1c, a number of interventions with the lowest end-impact (identified in step 1b) are selected and nominated to the optimisation step (i.e. step 2). Here 10 interventions are selected, because this number is considered adequate to provide sufficient response plan for a small network such that of C-Town, as well as the total time required for evaluation can be conducted in near real-time. This lies on the fact that a single impact evaluation takes approximately 3 sec to take place for the simple network of C-Town. Hence, step 1b, which includes 247 single impact evaluations (see above), lasts for 247 (interventions) x 3 sec (time of a single impact evaluation) = 741 sec. Considering that steps 1a and 1c take approximately 1 min each (because they do not require hydraulic simulation), then the overall preparation in step 1 takes approximately 14 mins.

The end-impact (in absolute value) and cost (in £) of the 10 candidate interventions (i.e. overland bypasses in 10 different locations) for start time 9am are shown in

Table 5-1. It is stressed that in the cost function in Eq. 7, only the cost of the overland bypasses has been used (assuming c_{OLB} = 30£/hour, obtained by the utility), because this is the only intervention type nominated for the next step of optimisation.

Table 5-1: End-impact and cost (£) of single interventions for the C-Town event

Intervention type		Start time	
		2am	9am
	End-impact	0.0863	-

No intervention	Cost	0	-
OLB1	End-impact	-	0.0744
	Cost	-	540
OLB2	End-impact	-	0.0745
	Cost	-	540
OLB3	End-impact	-	0.0663
	Cost	-	540
OLB4	End-impact	-	0.0856
	Cost	-	540
OLB5	End-impact	-	0.0838
	Cost	-	540
OLB6	End-impact	-	0.0809
	Cost	-	540
OLB7	End-impact	-	0.0814
	Cost	-	540
OLB8	End-impact	-	0.0862
	Cost	-	540
OLB9	End-impact	-	0.0862
	Cost	-	540
OLB10	End-impact	-	0.0862
	Cost	-	540

In step 2a of the heuristic, the initial solution is identified by the algorithm as the single intervention with the lowest cost. In

Table 5-1 it can be observed that the cost of all interventions is equal to £540, because they are all the same intervention type, i.e. overland bypass, starting at the same time. Hence, the single solution OLB3 (that obtains the lowest end-impact (i.e. equal to 6.63%) is selected as the initial solution (i.e. Solution 1).

Then, in step 2b of the heuristic algorithm, the subsequent solution is identified as the single solution with the lowest end-impact among all interventions. In this example, the solution with the lowest end-impact has already been used, hence the lowest end-impact of the rest of solutions is identified. In

Table 5-1, it is shown that the next lowest end-impact is equal to 7.44% obtained by OLB1 (Solution 2). This solution does not reduce the end-impact (i.e. at least one of the two objectives) and hence it is rejected. In the subsequent solution (i.e. Solution 3) the single intervention with the next lowest end-impact is added to Solution 1 (i.e. the last accepted solution). As noticed in

Table 5-1, OLB2 obtains the next lowest end-impact (equal to 7.45 %) and is added to Solution 1. Hence, Solution 3 is the combination of OLB3 and OLB2. Table 5-2 shows the end-impact and cost of all the solutions (i.e. intervention combinations) identified by the heuristic. It is observed that Solution 3 with end-impact equal to 6.77% and cost £1080 does not further reduce end-impact or cost comparing to Solution 1 and hence it is rejected. Because Solution 3 is rejected, in subsequent Solution 4, OLB2 is not considered and the single intervention with the next lowest end-impact is added. In

Table 5-1 it is observed that OLB6 obtains the next lowest end-impact and is combined with OLB3 in Solution 4. Now, Solution 4 does further reduce end-impact comparing to Solution 1, and hence it is accepted, as shown in Table 5-2. The same process is followed until all the single interventions have been added (i.e. after 10 iterations, as shown in Table 5-2).

Table 5-2: Solutions identified by the heuristic algorithm for the C-Town event compared to the 'No intervention' case and optimal solutions proposed by Mahmoud et al. (2018)

Solutions/Iterations	**End-impact (%)**	**Cost (£)**

No intervention	8.63	0	
Solution 1 (OLB3)	**6.63**	**540**	**accept**
Solution 2 (OLB1)	7.44	540	reject
Solution 3 (OLB3/OLB2, t=9am)	6.77	1080	reject
Solution 4 (OLB3/OLB6, t=9am)	**6.08**	**1080**	**accept**
Solution 5 (OLB3/OLB6/OLB7, t=9am)	6.08	1620	reject
Solution 6 (OLB3/OLB6/OLB5, t=9am)	**6.07**	**1620**	**accept**
Solution 7 (OLB3/OLB6/OLB5/OLB4, t=9am)	**5.98**	**2160**	**accept**
Solution 8 (OLB3/OLB6/OLB5/OLB4/OLB8, t=9am)	5.98	2700	reject
Solution 9 (OLB3/OLB6/OLB5/OLB4/OLB9, t=9am)	5.98	2700	reject
Solution 10 (OLB3/OLB6/OLB5/OLB4/OLB10, t=9am)	5.98	2700	reject
Solution A (Mahmoud et al. 2018) (OLB3,t=9am)	6.63	540	
Solution B (Mahmoud et al. 2018) (OLB3/OLB1,t=9am)	6.84	1080	

The 10 solutions proposed by the heuristic algorithm (shown in Table 5-2) are finally checked for optimality in step 2j online. This implies that each proposed solution should not be better than another solution (i.e. Pareto front). It is noticed that the accepted solutions in Table 5-2 are already the optimal ones and are the final solutions included in the Pareto front. Finally, step 2 includes 10 more impact evaluations, i.e. it lasts for 10 (evaluations) x 3 sec (time of a single impact evaluation) = 30 sec. This means that the total duration of the application of the optimisation method for the C-Town network is approximately 15 mins (i.e. 14 mins from step 1 and 30 sec from step 2).

In Table 5-2, the Pareto front of near optimal solutions is presented as the accepted solutions (i.e. bolded text). It is noticed that as expected on a Pareto front, each solution is not better than the other one, because a cheaper solution obtains higher end-impact and vice-versa. This means that operators have to decide the best solution based on their own criteria, which might depend on the value of specific impact indicators of a response solution, the highest expenses they wish to make for a response solution, etc. For example, if they gave priority to reduce the impact indicator of CML, then they would select a response solution from the Pareto front with the lowest value of CML even though this solution obtained higher total end-impact comparing to other solutions. The tool is able to provide the user with the values of each impact indicator for a specific solution on the Pareto front, as shown in the following Figure 5-3.

After the implementation of the optimisation method proposed here, the NSGA II is conducted for the same event. The NSGA II results (for the C-Town event) are compared with the results of the optimisation method proposed here in order to identify the reliability of the method. The considered interventions, the impact horizon and optimisation objectives are the same as used in the heuristic. More specifically, the decision variables of the heuristic are the 10 overland bypasses identified in step 1 of the optimisation method. However, NSGA II here considers the start time of each intervention a variable too (i.e. in the range of 1 hour and 24 hours after detection). This is done in order to indicate the error introduced by the limitation of heuristic (i.e. where a fixed start time is assumed). Additionally, the optimal solutions (i.e. combinations of overland bypasses) identified by Mahmoud et al. (2018) are assessed here (i.e. in the environment of IRPT) for their total end-impact (i.e. considering all aforementioned impact aspects) and for their cost. It is reminded here that Mahmoud et al. (2018) identified these optimal solutions by assessing impact of undelivered water (only) and number of interventions (i.e. not cost), and also by using NSGA II. Figure 5-3 compares the results obtained by the NSGA II (Pareto front) of the present optimisation problem, the Heuristic Pareto front of near optimal solutions, the Heuristic dominated (i.e. rejected) solutions, the ‘No intervention’ case and the solutions obtained by Mahmoud et al. (2018).

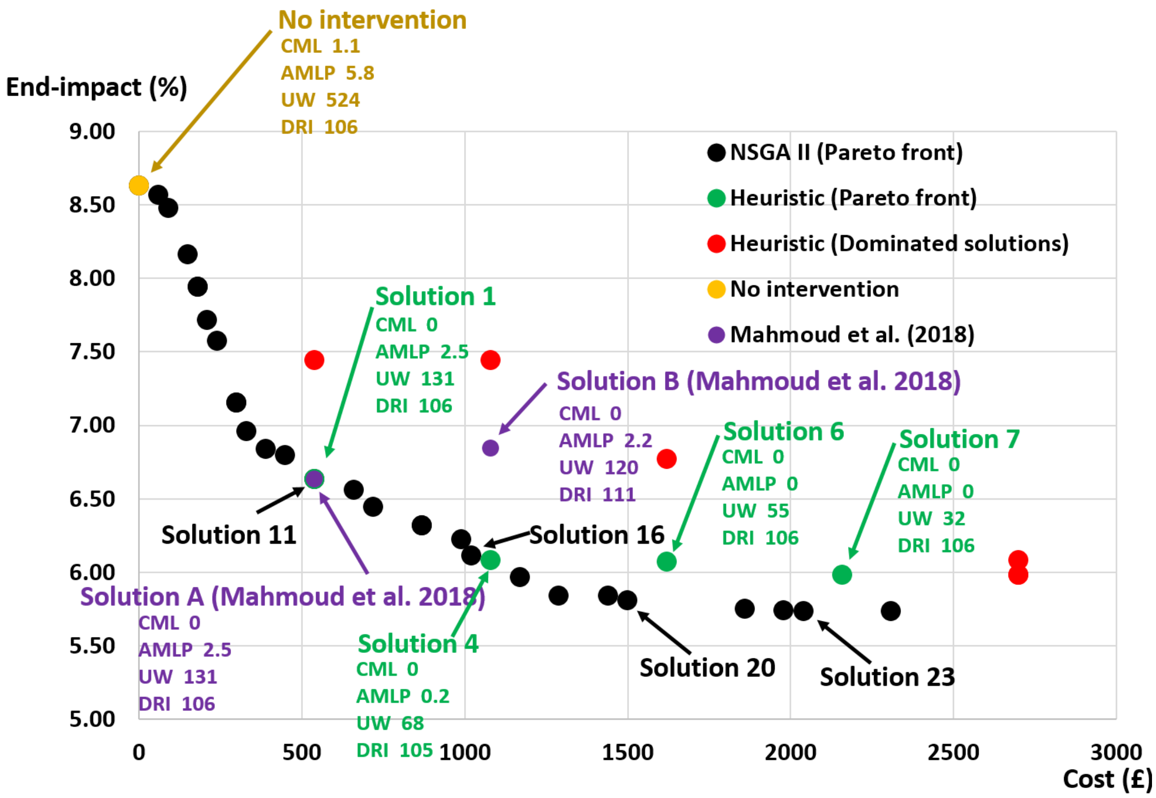

Figure 5-3: End-impact vs cost of the solutions for the C-Town event identified by NSGA II (Pareto front), the Heuristic (Pareto front and dominated solutions) and Mahmoud et al. (2018) - CML in mins/cust AMPL in mins/cust, UW in m^3 and DRI in no. of pipes

Based on the results shown in Table 5-2 and Figure 5-3 the following observations are made:

- The Pareto front identified by the heuristic sufficiently approximates the NSGA II Pareto front, as the maximum discrepancy (i.e. error) of end-impact between a NSGA II and a heuristic solution with similar costs (e.g. Solution 6 of heuristic compared to Solution 20 of NSGA II and Solution 7 of heuristic compared to Solution 23 of NSGA II) is equal to 4%.
- The Pareto optimal front identified by the heuristic is less dense than the Pareto front proposed by the NSGA II. Hence, only 4 near-optimal solutions are proposed by the heuristic compared to the 24 solutions proposed by the NSGA II. However this is not deemed significant drawback of the optimisation method, because all the proposed solutions are near-optimal. Additionally, it is believed here that in near real-time in a

control room there is limited time available to check a big number of optimal solutions.

- The optimisation process (i.e. online selection of population and heuristic) took approximately 15 minutes, whereas the NSGA II in the context of this case study took approximately 3 hours. Additionally, Mahmoud et al. (2018) required 30 minutes to solve the same optimisation problem (but for a fixed start time of interventions). Hence, the time that the proposed optimisation (with similar search space as in Mahmoud et al. 2018) was completed here is less than the last study, as well as less than the NSGA II in the context of this study.
- In Table 5-2 and Figure 5-2 it is observed that all the overland bypasses identified in the accepted solutions (i.e. OLB3, OLB4, OLB5 and OLB6) are located in the affected DMA1, close to the affected nodes and isolated area (i.e. burst event). Hence it is confirmed the obvious point that bypassing affected nodes with unaffected nodes in the affected DMA and close to the isolated area can significantly reduce end-impact.
- The NSGA II Solution B identified in Mahmoud et al. (2018) managed to reduce the undelivered water (i.e. their sole impact indicator) to 120 m^3. However, the heuristic method identified solution (i.e. Solution 7) where the undelivered water was reduced to 32 m^3. This is due to the fact that the heuristic optimised not only the undelivered volume of water, but also additional impact aspects (e.g. CML, AMLP) whose reduction facilitates the reduction of undelivered water.
- In Mahmoud et al. (2018) Solution A and Solution B are the non-dominated solutions in their proposed NSGA II Pareto front. Hence, in their study, Solution B obtains lower end-impact (i.e. undelivered water volume, first objective) and bigger number of interventions (i.e. second objective) than the Solution A. However, in Figure 5-3 it is shown that when end-impact with more than one impact aspects is considered, Solution B is dominated by Solution A. This is due to the fact that although UW was reduced to 120 m^3 in Solution B (compared to 131 m^3 in Solution A) and AMLP was reduced to 2.2 mins/cust in Solution B (compared to 2.5 mins/cust in Solution A), when increasing the number of interventions DRI was

increased (from 106 in Solution A to 111 in Solution B). This ultimately caused the increase of the total aggregated end-impact of Solution B (instead of decreasing it as anticipated in a Pareto front).

In Table 5-3 the two solutions identified by the heuristic and NSGA II (conducted here) with similar cost and end-impact are compared. This is done in order to point out the difference in interventions and/or start times that cause these small end-impact discrepancies. In Table 5-3, as far as the first comparison is concerned, it is observed that the NSGA II identified Solution 11 with exactly the same end-impact with Solution 1 (by heuristic) for the same cost and also by using the same overland bypass (i.e. OLB3) (at the same start time). As far as the second comparison is concerned, it is seen that the NSGA II identified Solution 16 with end-impact higher than the one in Solution 4 (by heuristic) but for lower cost. Hence no solution is better than the other. However it is worth noticing that the heuristic although its limitations identified a solution that with slight increase in cost (i.e. from £1020 in NSGA II to £1080 in heuristic) reduced the total aggregated end-impact. In these two solutions different overland bypasses and start times were used. This is anticipated in cases where different end-impact and cost values are identified in solutions from different methods. The overland bypasses used in the above solutions are shown in Figure 5-2.

Table 5-3: Comparison of solutions with the same cost and slightly different end-impact between heuristic and NSGA II for the C-Town event

	Comparison 1		**Comparison 2**	
Optimisation method	Heuristic	NSGA II	Heuristic	NSGA II
Solution	Solution 1	Solution 11	Solution 4	Solution16
Cost (£)	540	540	1080	1020
End-impact (%)	6.63	6.63	6.08	6.11

Interventions/ start time (hours)	OLB3,9am	OLB3,9am	OLB3,9am /LB6,9am	OLB4,5pm/ OLB6,1am (next day)

5.2.1 Sensitivity analysis

In the context of the C-Town case-study, a sensitivity analysis is conducted in order to test different start times of interventions. This sensitivity analysis aims to investigate the robustness of the optimisation method to the interventions' start time. As it was mentioned earlier, the optimisation method proposes a (selected by operator) fixed start time (here assumed as 9am) due to time limitation to test different start times in near real-time.

In the context of this sensitivity analysis, five more start times close to the selected one here (i.e. 9am) are tested, i.e. at 6am, 7am, 8am, 10am and 11am. The above additional start times are considered here to be adequate to conduct the sensitivity analysis. This is due to the fact that they are all morning hours (i.e. with similar demands) close to the initially selected one (i.e. some start times earlier than 9am and some start times later than 9am). Consideration of much later hours (i.e. after 12pm) might produce results substantially deviated from the original start time due to different demand levels. The results are shown in Figure 5-4 and are compared with the NSGA II results.

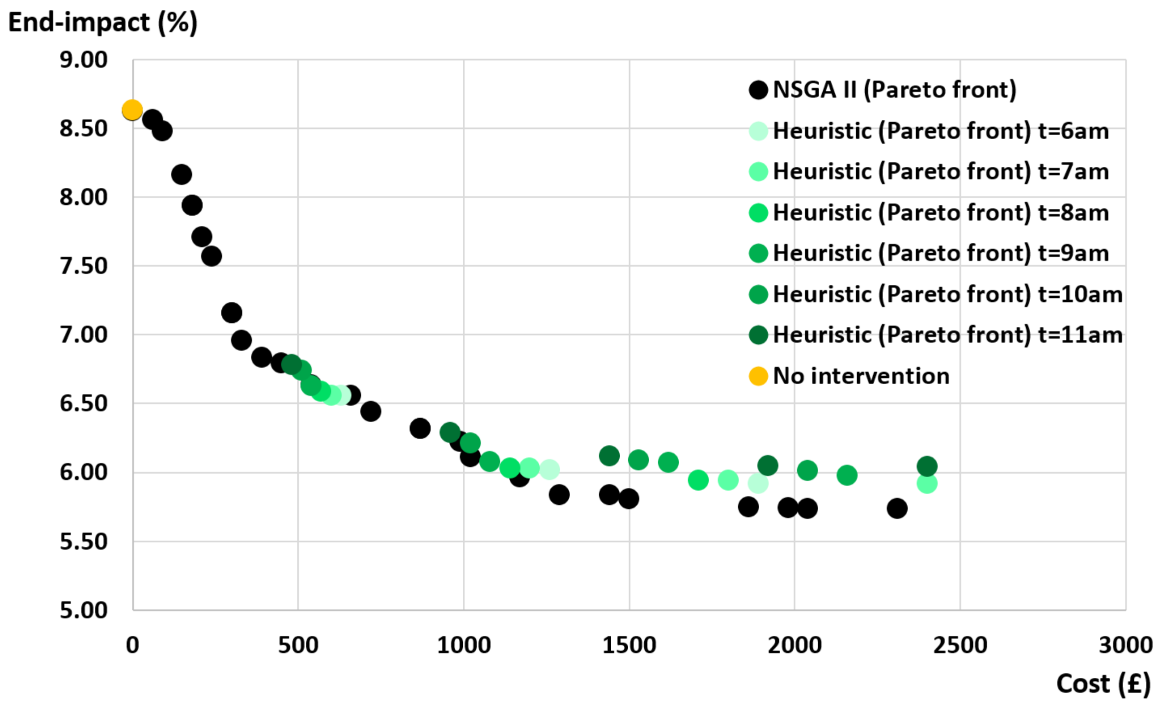

Figure 5-4: Solutions of different start times identified by the optimisation method (i.e. heuristic) for the C-Town event

From Figure 5-4 it is observed that:

- The Pareto front obtained using the heuristics algorithm approximates the NSGA II front reasonably well, especially for the most important part with lower cost solutions. Indeed, for lower costs (i.e. lower than £1500) and for all the start times the heuristic approach identifies solutions that are almost identical to the NSGA II. For higher costs (i.e. higher than £1500), heuristic solutions are dominated by the NSGA II solutions but not by much, i.e. the distance between the two Pareto fronts is rather small with heuristic solutions with earliest start times (i.e. 6am and 7am) being closer to the NSGA II solutions.
- The following overland bypasses exist in all heuristic solutions, regardless of the start time used: OLB3, OLB4 and OLB6. This is good news as these overland bypasses are the most important ones, as confirmed by the NSGA II solutions.

5.3 P-Town case study

In this section, the optimisation method is tested on the P-Town case study. The steps of the optimisation method for the P-Town network and event have already been applied in chapter 4. Hence, in this section the heuristic solutions are compared to the NSGA II results (conducted in the context of the present case study). As mentioned in chapter 4, the P-Town real-life event is a WTW shutdown detected/localised at 2pm on 2nd November 2019. The shutdown lasted for 24 hours (i.e. until 2pm next day). The impact horizon considered here lasts from the detection/localisation time (i.e. 2pm first day) until the end of shutdown/isolation (i.e. 2pm next day), i.e. 24 hours horizon.

After the implementation of the optimisation method for the P-Town case study in chapter 4 (see sub-section 4.3.4), the NSGA II is conducted here for the same event in order to compare the results between the two optimisation methods. The considered interventions, the impact horizon and the optimisation objectives are the same as used in the heuristics based method. More specifically, the decision variables of the heuristic are the 5 rezoning valves and 5 ASVs identified in step 1 of the optimisation method (see Figure 4-1). Additionally, the same indicators weights as the ones used for the impact assessment in the heuristic are used: w_{CML}=0.4, w_{AMLP}=0.15, w_{UW}=0.3 and w_{DRI}=0.15.

However, NSGA II here considers the start time of each intervention a variable too (i.e. in the range of 1 hour and 23 hours after detection). This is done in order to indicate the error introduced by the limitation of the method (i.e. assuming a fixed start time). It is highlighted that consideration of start time of 1 hour after event detection/localisation in the NSGA II might not be realistic (even in the heuristic method where optimisation is conducted in some minutes), because the response decision-making process takes approximately 1 hour, and then about 1 more hour is required for the technicians mobilisation. However, this start time is considered here for completeness.

In Figure 5-5 the end-impact and cost of the solutions for the P-Town event identified by the NSGA II (Pareto front), the Heuristic (Pareto front and dominated solutions) and the ‘No intervention’ case are compared. In Figure 5-5 it is observed:

- The Pareto front identified by the heuristic approximates the NSGA II Pareto front well, as the maximum discrepancy (i.e. error) of end-impact between a NSGA II and a heuristic solution with similar costs (e.g. Solution 7 of heuristic compared to Solution 16 of NSGA II) is equal to 9%. It is noticed that the error in the P-Town case-study is higher than the error in the C-Town (i.e. 4%). However it is deemed low considering the significant limitation of the fixed start time for the present complex real-life network.
- The method also identified the 'jump' from a solution with high end-impact (i.e. Solution 1) to a solution with much lower end-impact (i.e. Solution 2) with minimum cost increase. Solutions like these (i.e. Solution 2) are likely to be selected by decision-makers. It is also observed that Solution 2 seems identical to the solution proposed by NSGA II (i.e. Solution 5).
- Similarly to the C-Town case-study, the Pareto optimal front identified by the heuristic is less dense than the Pareto front proposed by the NSGA II. Hence, only 7 (non-dominated) near-optimal solutions are proposed by the heuristic compared to the 20 solutions proposed by the NSGA II. However as mentioned earlier this is not deemed as a significant drawback of the optimisation method, because the front coverage is good and, also, in near real-time, in a control room there is limited time available to check a large number of optimal solutions.
- NSGA II was conducted here (with search space equal to 2^{10} x 23^{10}=4 x 10^{16}) and took approximately 2 days to be completed, while the optimisation process (i.e. online selection of population and heuristic) took approximately 1 hour (see sub-section 4.3.4). Hence, the time that the proposed heuristic optimisation was completed here is much less than the NSGA II.

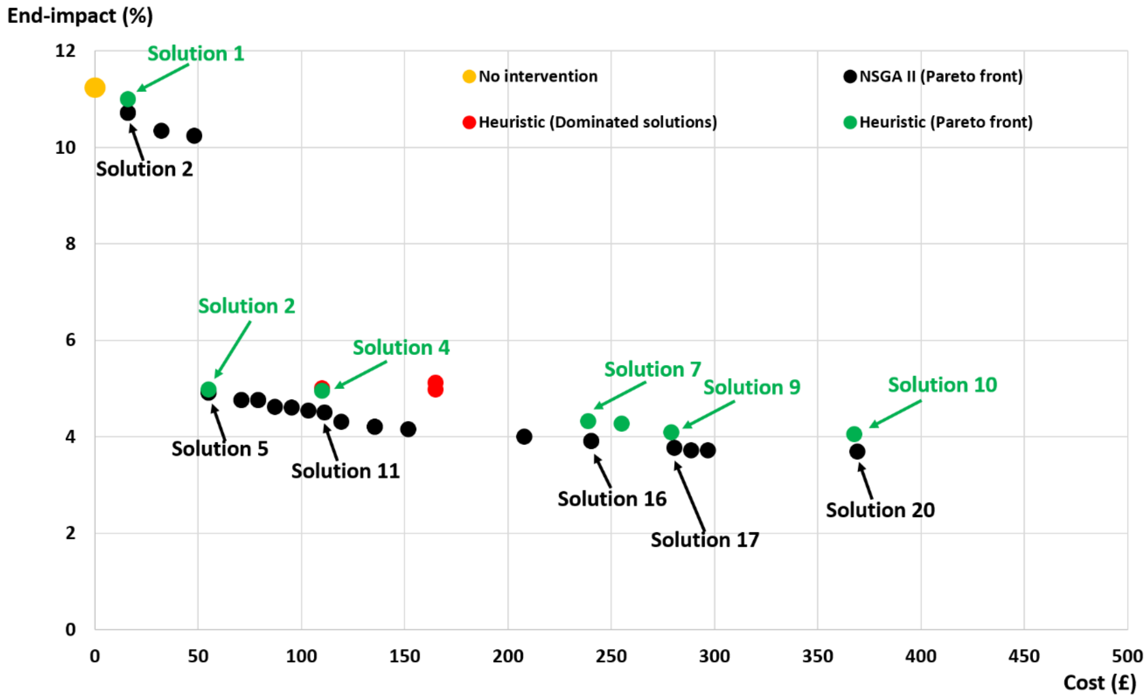

Figure 5-5: End-impact vs cost of the solutions for the P-Town event identified by NSGA II (Pareto front) and the Heuristic (Pareto front and dominated solutions)

In Table 5-4 the solutions identified by the heuristic and NSGA II (conducted here) with similar cost and end-impact are compared. This is done in order to point out the difference in interventions and/or start times that causes these small end-impact discrepancies. Most of the discrepancies regard the start time of interventions, which is due to the fact that NSGA II optimised for different start times (unlike the heuristic method where a fixed start time was considered).

In Table 5-4, as far as the first comparison is concerned, it is observed that the NSGA II Solution 2 obtains the same cost with the heuristic's Solution 1, but with (slightly) lower end-impact (as anticipated). NSGA II solution 2 identified a single ASV to implement (i.e. ASV6) similarly to the heuristic's solution 1, but for a later start time. Similarly to the first comparison, in the second comparison the NSGA II solution 5 obtains a lower end-impact than the heuristic's solution for the same cost. Comparison 3 to comparison 6 present heuristic solutions with higher end-impact than the NSGA II solutions, but with lower cost. Hence, in comparison 3 to comparison 6 the NSGA II solutions are not better than the heuristic's solutions.

For example, in comparison 3, the NSGA II solution 11 obtains end-impact equal to 4.5%. Although NSGA II's end-impact is lower than the end-impact of the heuristic's solution 4 (i.e. 4.95%), the cost of the NSGA II solution is higher (i.e. £111.44 > £110.04). Additionally, it is observed that in comparison 3 and 4 the heuristic solutions were obtained for less number of interventions. In comparison 5 and 6 the number of proposed interventions by the heuristic is the same as the one proposed by the NSGA II.

From the above observations, it is concluded that in the heuristic solutions the number of proposed interventions does not overcome the number of interventions identified by the NSGA II (in many cases the number proposed by the heuristic is smaller). This might be an advantage for utilities in case of limited resources during the response decision-making.

Table 5-4: Comparison of solutions with similar costs and slightly different end-impact between heuristic and NSGA II for the P-Town event

	Comparison 1		**Comparison 2**	
Optimisation method	Heuristic	NSGA II	Heuristic	NSGA II
Solution name	Solution 1	Solution 2	Solution 2	Solution 5
Cost (£)	16.12	16.12	55.02	55.02
End-impact (%)	11.0	10.71	4.97	4.91
Interventions/ start time (hours)	ASV5,t=4pm (same day)	ASV6,t=2am (next day)	V4,t=4pm (same day)	V4,t=3pm (same day)
	Comparison 3		**Comparison 4**	
Optimisation method	Heuristic	NSGA II	Heuristic	NSGA II

Solution name	Solution 4	Solution 11	Solution 7	Solution 16
Cost (£)	110.04	111.44	239	240.4
End-impact (%)	4.95	4.5	4.31	3.9
Interventions/ start time (hours)	V4/V3,4pm (same day)	V4,3pm/ASV3,11pm/ASV5,10pm/ASV6,7pm (same day)	V4/V3/ASV1,4pm (same day)	V4,3pm/ASV1,3pm/ASV3,11pm/ASV5,3pm/ASV6,7pm (same day)
	Comparison 5		**Comparison 6**	
Optimisation method	Heuristic	NSGA II	Heuristic	NSGA II
Solution name	Solution 9	Solution 17	Solution 10	Solution 20
Cost (£)	279.3	280.7	367.96	369.36
End-impact (%)	4.09	3.77	4.05	3.68
Interventions/ start time (hours)	V4/V3/ASV1/ASV5/ASV6,4pm (same day)	V4,3pm/ASV1,3pm/ASV3,9pm/ASV5,2am (next day)/ASV6,3pm (same day)	V4/V3/ASV1/ASV5/ASV6/ASV4,4pm (same day)	V4,3pm/ASV1,3pm/ASV3,11pm/ASV5,3pm/ASV6,9pm/ASV4,11pm (same day)

5.4 Summary

This chapter presented the validation of the heuristic-based method for near optimal response to water network failures in near real-time. The validation was carried out by comparing the method's solutions with the solutions of the more advanced/accurate (but also time-consuming) NSGA II method. The method was validated on two case studies. The first case study considered here was the simple, real-life network of C-Town and the second one was the complex, real-life network of P-Town. For the C-Town case study, the heuristic solutions were also compared with the results of a past study, i.e. the Mahmoud et al. (2018), where conventional optimisation techniques (e.g. optimisation method and objective functions) were used. A sensitivity analysis was also conducted in order to investigate the robustness of the method to the start time of interventions.

In section 5.2, the optimisation method was applied step by step for the C-Town case study. After the identification of the solutions obtained with the heuristics method, the NSGA II was conducted for the same optimisation problem, but considering the start time of interventions as decision variable. The solutions obtained with the optimisation method were compared then with the NSGA II solutions as well as with the solutions obtained by Mahmoud et al. (2018) (where more conventional optimisation techniques have been used). In sub-section 5.2.1, different start time scenarios were tested and compared in order to investigate the sensitivity/robustness of the method to the start time of interventions. In section 5.3, the optimisation method's solutions were compared with the NSGA II solutions for the P-Town case study. Based on the above analyses the following key findings were obtained:

- The heuristics based method is able to identify near optimal response solutions in an effective (i.e. accurate) and efficient (i.e. computationally fast) manner. The effectiveness is confirmed by running the full, NSGA II based optimisation runs and comparing the resulting Pareto fronts which match well. The computational efficiency achieved enables its application in near real-time for larger, more complex WDS.
- The Pareto optimal front identified by the heuristics method has a good coverage, but it is less dense than the corresponding front obtained by the NSGA II. This, however is not deemed as a significant drawback, because

all solutions are proposed by the heuristics method in near real-time and are near-optimal. Furthermore, the set of solutions identified represents well the trade-off between the impact reduction and associated costs of responses. Therefore, the solutions identified provide a good starting point for consideration by control room operators who have a final say anyway.

- When compared to the solutions obtained by Mahmoud et al. (2018), the heuristics method managed to improve the quality of some of solutions (e.g. reduced the volume of undelivered water) despite the fact that its impact reduction is driven by other criteria as well. It also managed to reduce the time required for the identification of the final response plan to 15mins (for the simple network of C-Town).
- The potential drawback of the method is its inability to optimise for the start time of interventions which therefore needs to be set by the control room operator. Having said this, as demonstrated in both case studies, the solutions generated by the heuristics method are robust enough, i.e. rather insensitive to this start time.

6 SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

6.1 Summary

6.1.1 Thesis Summary

The water industry in the UK and abroad has a pressing need to better manage interruptions to water supply caused by various failures such as pipe bursts, equipment failures or WTW shutdowns. One way of doing this is by making use of the increasingly available real-time sensor data collected in WDSs, as well as by using hydraulic models in real-time. Currently, real-time sensor data and real-time hydraulic modelling are not used much in a water utility's control room, especially when it comes to identifying a suitable strategy to respond to failure events in near real-time.

The aim of this project was to develop, validate and demonstrate a new response methodology to support decisions made by control room operators when dealing with various failure events in a WDS. As an integral part of this work, an interactive decision-support tool called IRPT was developed in order to support/guide operators in identifying effective response solutions in near real-time (i.e. usually required up to 1 hour after the event detection/localisation). The tool was used in this thesis to test and validate the response methodology.

The response methodology proposed in this thesis consists of the following main steps: Step 1) initial impact assessment, Step 2) identification of the isolation plan, Step 3) manual identification of a response solution proposed by an operator, Step 4) automatic identification of a response solution generated using optimisation, and Step 5) identification of the response solution to be implemented in the field. These five steps do not need to be necessarily carried out in a sequential manner as presented here. An integral part of the response methodology is the development of a novel, heuristic-based, optimisation method for near optimal response to failures in WDSs in near real-time. The response problem was formulated as a two-objective optimisation problem with objectives being the minimisation of failure impacts and related operational costs. The heuristic-based method was used to solve this problem. For the first objective (i.e. impact assessment), a impact assessment method was developed, using realistic impact indicators and bearing in mind the UK water industry practice, as well as previous relevant literature (e.g. Bicik et al. 2009). The considered impact indicators cover different aspects of the event, such as water supply interruption, low pressure impact and discolouration risk increase impact. Furthermore, a consistent framework for end-impact assessment (i.e. same impact metrics calculated for every proposed response solution) was implemented in order to facilitate easy comparison between different response solutions.

The IRPT is developed in the MATLAB environment and links to EPANET2 for the execution of hydraulic simulations and to QGIS for the visualisation of the impact indicators on a map. In each of the five methodological steps, there is the first stage where the information is inputted into the tool by the operator (not hydraulic expertise is required). Then in the second stage the hydraulic simulations are conducted by calling the EPANET2 functions and the end-impact/cost is calculated. Finally in the third stage the impact indicators are visualised on a map.

In chapter 4 the response methodology was demonstrated and validated on a semi-real case study. Comparison between the ‘Current practice response’ (i.e. solution based on the current response practice of the utility) and the ‘New methodology response’ (i.e. solution identified after interaction with the IRPT) showed that the IRPT enabled operators identify a response solution with much lower values in all impact indicators (especially in DRI) and cost.

The heuristic-based method was validated on two case studies in chapter 5. The validation was carried out by comparing the method’s solutions with the solutions of the more advanced/accurate (but also time-consuming) NSGA II method. The first case study considered was the simple, real-life network of C-Town and the second one was the complex, real-life network of P-Town. For the C-Town case study, the heuristic solutions were also compared with the results of a past study, i.e. the Mahmoud et al. (2018), where conventional optimisation techniques (e.g. optimisation method and objective functions) were used. A sensitivity analysis was also conducted in order to investigate the robustness of the method to the start time of interventions.

6.1.2 Summary of Thesis Contributions

The main contributions (i.e. novelties) of the work presented in this thesis are as follows:

- A structured yet flexible and interactive response methodology supporting and guiding the operator throughout the entire response process, from detection and localisation of a failure event to implementation of the identified response solution in the field. The methodology supports the operator in making effective response decisions in near real-time by interacting with the IRPT (e.g. via 'what-if' scenarios) whilst allowing the operator to have a final say.
- A methodology that enables provision of automatically generated recommendations (i.e. near optimal response interventions) via a new heuristic optimisation algorithm enabling the operator to make better informed decisions.
- A impact assessment methodology that makes use of multiple impact indicators covering both water quantity and quality related aspects of the impact of different response solutions (including 'do nothing') on water distribution system performance following the failure event.
- Application and modelling of realistic operational interventions, in terms of availability of different types of interventions, start times for interventions' implementation, duration of interventions' implementation, all with associated operational cost models.

6.2 Conclusions

The main thesis conclusions are as follows:

- The response methodology works well, as demonstrated on the semi-real case study. The results obtained showed that the tool enabled operators to identify a more effective response solution (i.e. reduced end-impact and cost) compared to the solution based on the current response practice.

This is because the tool allowed operators to compare alternative response strategies (i.e. manually created by the operator and automatically generated by the IRPT through optimisation). This comparison was facilitated by the consistent impact assessment (i.e. same metrics assessed for each solution) used in the tool, as well as by the comprehensible impact metrics (i.e. well-known metrics in utilities), impact coverage (shown in maps) and cost of different solutions (shown in graphs).

- The response solution was identified by the tool within 1 hour after the event detection/localisation (i.e. in near real-time under the assumption that no unpredictable event has occurred on site). This was accomplished in a complex, real-life network, hence increasing the potential of water utilities making use of the tool in real-life.
- The heuristic-based optimisation method, as demonstrated on the two case studies, was able to identify near optimal response solutions in an effective (i.e. accurate) and efficient (i.e. computationally fast) manner. The effectiveness was confirmed by running the full, NSGA II based optimisation runs and comparing the resulting Pareto fronts which matched well. Hence, the computational efficiency of the optimisation method enables its application in near real-time for larger, more complex WDS.
- The Pareto optimal front identified by the heuristics method had a good coverage, but it was less dense than the corresponding front obtained by the NSGA II. This, however, is not deemed as a significant drawback, because all solutions proposed by the heuristics method are near-optimal and the set of solutions identified represents well the trade-off between the impact reduction and associated costs of responses. Therefore, the solutions identified provide a good starting point for consideration by control room operators who have a final say anyway.
- When compared to the solutions obtained in published literature, the heuristic-method managed to improve the quality of some of solutions (e.g. reduced the volume of undelivered water) despite the fact that its impact reduction is driven by other criteria as well. It also managed to reduce the

time required for the identification of the final response plan to 15mins (for the simple network of C-Town).

- The potential drawback of the heuristic-based method is its inability to optimise for the start time of interventions which therefore needs to be set by the control room operator. Having said this, as demonstrated in both case studies, the solutions generated by the heuristics method are robust enough, i.e. rather insensitive to this start time.

- The tool presented here (i.e. the IRPT) includes only the step of response methodology and not the rest of steps of the event management process, i.e. the detection and localisation. Detection and localisation are not the focus of this study, because they have been extensively studied in the past (see chapter of Literature Review). However, including them in the IRPT would create an integrate event management tool for utilities. This would enable them to react in an even faster way, because the detection/localisation details (e.g. event type, exact location, event magnitude, etc.) would be automatically entered in the tool database (and not manually as done in this thesis).

6.3 Anticipated outcomes and benefits

The new technology developed in this thesis is anticipated to allow United Utilities and other water companies in the UK and abroad to further improve their service which, in turn, will result in improved quality of life in cities, improved preservation of natural resources, better protection of the environment and improved sustainability.

The following key benefits are envisaged for the sponsoring organisation and other stakeholders:

- Improved customer service and reduced customer complaints and regulatory fines associated with the impacts of WDS events.

- Reduced operational and maintenance costs via improved awareness and handling of events.

- New technology giving United Utilities the cutting edge on the UK and worldwide water engineering markets.
- Wider application of the technology, e.g. in wastewater networks, and associated benefits.
- Encouraging and speeding up the cultural change in the water sector required for the implementation of smart water technologies. This is associated with the need of water utilities nowadays to go one step further and adopt new technologies for the benefit of the environment (e.g. less water lost due to bursts), the society (e.g. less complaints and safer/uninterrupted water supply) and the utility (e.g. less fines due to incompliance to regulators). The cultural change can be achieved through investing in research of new technologies and the education of employees.

6.4 Future research

This section suggests possible directions of further research to extend and improve the work presented in this thesis. The proposed recommendations for future investigation are given separately in different sections, based on the different constituents of the response methodology.

6.4.1 Response methodology framework

An integral part of the proposed response methodology and interactive tool is the visualisation/presentation of the identified response plan to the control room operators (i.e. the third stage of the response methodology at every step, see chapter 3). Currently in this thesis, the identified response plan is visualised through maps (showing selected impact aspects of a response plan, e.g. Figure 4-3) and graphs (showing pressure timelines, pressure vs cost curves and Pareto fronts of near-optimal solutions, e.g. Figure 4-3 and Figure 4-4). Furthermore, when several response solutions are proposed, these are visualised through a single window to facilitate easy comparison (e.g. Figure 4-5). At the moment, the user inputs in the tool the impact aspect to visualise on the map and a desired node for which the pressure timeline is presented. Hence the visualisation of (one or more) response solution(s) to the operators could be improved in the following way:

- The maps could be interactive, allowing operators select for example on the map the impact aspect to view or a specific node to view the pressure timeline. These interactive maps would enable faster visualisation of different response solutions and/or impacts, and hence easier comparison. Moreover, 3D visualisation software could be used, enabling different impact aspects of one solution or one impact aspect of different solutions to be visualised along the different dimensions in a single figure (for easier comparison). Finally, when a selected impact aspect of a response solution is visualised on the map, the intervention locations could also be visualised on the same map. This would be particularly useful when operators propose manually ‘what-if’ scenarios. For example, if operators wish to reduce impact on a specified area of the network, visualisation of interventions location on the map would allow them to select the interventions located closer to their desired area (i.e. increasing the potential of reducing impact to this area).

6.4.2 Impact assessment

The impact assessment method proposed in this thesis could be improved with the following ways:

- Consideration of more impact aspects in the calculation of the total, aggregated end-impact of a response solution. In the impact assessment of this thesis, the impact aspects covered are related to supply interruption, low pressure and discolouration risk increase. However, a real-life failure event and/or the follow-on interventions might cause additional negative impacts, such as environmental impact, 3rd party damage, traffic impact, etc. It is stressed that any other impact aspect can be easily incorporated in the current impact assessment method if it can be normalised, in order to calculate the total, aggregated end-impact.
- Improvement of the discolouration risk increase (DRI) index. In this work, the estimation of DRI index considers only the flow velocity and flow rate.

The improved DRI index could take into account several other factors that affect the accumulation of particles into the pipeline, such as the flow direction, the pipe material, etc.

6.4.3 Hydraulic modelling

The hydraulic modelling used in this thesis could be improved or extended with the following ways:

- Improvement of ASV injection modelling. For the purposes of this thesis, the ASV water injection was modelled as injection from water trucks (i.e. tanks in the hydraulic model) with total volume equal to $90m^3$, i.e. equal to 3 tanks of $30m^3$ each. The water injection was modelled to take place once, i.e. until the water volume of $90m^3$ has been injected into the network. However, in real-life larger volumes of water might be required to restore supply at some nodes and/or more than once in the day (depending on the time of the day and demand requirements of the node). Water injection then could be improved by modelling water injection from a number trucks of $30m^3$ (depending on the demand requirements) at different times in the day.
- Use of alternative pressure-driven model. The pressure-driven model currently used in the proposed response methodology is the Paez et al (2018), as it has proven to work well on larger networks. It is stressed that use of alternative (e.g. more advanced or recent) pressure-driven models was not used here, because this is not the focus of this thesis. The focus is on the optimisation part of the response methodology. Recent advancements on the development of pressure-driven models include the EPANET 2.2 released in July 2020. The proposed response methodology is generic in a sense that any other pressure driven model can be used instead of Paez et al (2018) if preferred.

6.4.4 Optimisation

The heuristic-based optimisation method proposed in this thesis could be improved with the following ways:

- Consideration of the start time of interventions as a decision variable. Currently in this thesis, the optimisation problem considers as decision variables only the interventions status (i.e. interventions used or not used). All of the interventions identified by optimisation are supposed to be implemented at a fixed time in the horizon (specified by operators at the beginning of simulations). More specifically, the decision variables considered are the status of rezoning valves (i.e. open or close), the status of overland bypasses (i.e. open or close), the setting of PRVs (i.e. no increase, 5% increase, 10% increase, 15% increase, 20% increase, or 25% increase, all relative to the original PRV setting) and the status of ASV valves (i.e. open or close). However, in real-life more than one interventions might be selected in a response plan. In such case, each intervention should start at a different time in the horizon due to (larger or smaller) distance between the different intervention locations. Optimisation then should consider the start time of each intervention as a decision variable to make the response plan identified by optimisation more realistic.
- Development of a more advanced and automatic process for selection of the initial population (i.e. step 1 of the heuristic-based optimisation method). Currently, the present optimisation method's first online step is the manual narrowing-down of the initial list of available interventions (found in the offline step). This manual process includes: (a) an initial impact assessment and identification/visualisation of the affected DMAs/nodes and then (b) manual selection of interventions which link to affected areas. Although this technique is realistic (i.e. based on engineering judgement and experience), it does not automate the process followed in the first online step of the present optimisation method. Alternative automatic techniques for the selection of initial population found in the published literature could be used instead. These techniques usually require pre-optimisation hydraulic simulations, such as running the

optimisation problem with hydraulic analysis only for a number generations (via an advanced/accurate optimisation method such as NSGA II) and using the optimal solutions as initial population subsequently. However it is believed here that such techniques although automatic, they do not guarantee faster (i.e. near real-time) identification of optimal solutions, due to time-consuming hydraulic runs (especially in large, complex networks).

6.4.5 Validation of the response methodology

The validation of the proposed response methodology in this thesis could be improved with the following way:

- Further testing and validation of the proposed response methodology on additional real-life case studies involving alternative/more complex failure events and associated responses. In this thesis, the response methodology was demonstrated and validated on a semi-real event, i.e. a WTW shutdown (obtained by water utility). Based on the results, it was shown that the response methodology works well for such events, as the tool enabled operators to identify a more effective response solution compared to the solution based on the current response practice. However, the response methodology could be validated on alternative real-life events, such as equipment failures or major pipe bursts, in order to demonstrate its generic nature and the potential to be used by water utilities on any type of event. This was not conducted in the present thesis due to time limitation.

BIBLIOGRAPHY

Papers presented by the candidate

Nikoloudi, E., Romano, M., Memon, F. A., & Kapelan Z. (2021). Interactive Decision Support Methodology for Near Real-time Response to Failure Events in a Water Distribution Network. *Journal of Hydroinformatics, 23(3), 483-499*.

Nikoloudi, E., Romano, M., Memon, F. A., & Kapelan Z. (2021). Heuristic-based Approach for Near-Optimal Response to Water Network Failures in Near Real-Time. *Journal of Water Resources Planning and Management* (submitted).

Paez, D., Filion, Y., Castro-Gama, Quintiliani, C., Santopietro, S., Butler, D., Farmani, R., Fu, G., Meng, F., Sweetapple, C., Diao, K., Huang, Y., Ulanicki, B., Zhang, Q., Zheng, F., Abraham, E., Deuerlein, J., Gilbert, D., Piller, O., Balut, A., Brodziak, R., Bylka, J., Zakrzewski, P., Cai, J., Chenhao, O., Jinliang, G., Shiyuan, H., Yuanzhe, L., Mahmoud, H. A., **Nikoloud**i, E., Romano, M., Sophocleous, S., Woodward, K., Creaco, E., Di Nardo, A., Di Natale, M., Santonastaso, G.F., Bibok, A., Aguilar, A., Cuero, P., Gonzalez, S., Muñoz, S., Pérez, J., Posada, A., Robles, J., Salcedo, C., Vargas, K., Franchini, M., Galelli, S., Hoon Kim, J., Iglesias-Rey, P., Kapelan, Z., Saldarriaga, J., Savic, D., & Walski, T., (2020). The Battle of Post-Disaster Response and Restoration (BPDRR). *Journal of Water Resources Planning and Management*, 146(8), 04020067.

Nikoloudi, E., Romano, M., Memon, F. A. & Kapelan, Z. (2020). Event Management and Event Response Planning for Smart Water Networks: UK case study. *In 14th International Conference on Hydroinformatics (HIC)*, Mexico City, Mexico (submitted)

Sophocleous, S., **Nikoloudi**, **E**., Mahmoud, H. A. & Romano, M. (2018). Simulation-based framework for the restoration of earthquake-damaged water distribution networks using a genetic algorithm. *In WDSA/CCWI Joint Conference Proceedings*, 1.

List of references

Alfonso, L., Jonoski, A., & Solomatine, D. (2010). Multiobjective optimization of operational responses for contaminant lushing in water distribution networks. *J. Water Resour. Plann. Manage.* 136 (1): 48–58.

Azimirad, E., & Haddadnia, J. (2015). The comprehensive review on JDL model in data fusion networks: techniques and methods. *International Journal of Computer Science and Information Security,* 13(1), 53.

Bajpai, S., & Gupta, J. P. (2007). Securing oil and gas infrastructure. *Journal of Petroleum Science and Engineering*, 55(1), 174-186.

Beale, E. M. (1979). Branch and bound methods for mathematical programming systems. In *Annals of Discrete Mathematics*, 5, 201-219.

Bicik, J., Makropoulos, C., Joksimović, D., Kapelan, Z., Morley, M. S., & Savić, D. A. (2008). Conceptual risk-based decision support methodology for improved near real-time response to wds failures. In *Water Distribution Systems Analysis*, 1-10.

Bicik, J., Kapelan, Z., & Savić, D. A. (2009). Operational perspective of the impact of failures in water distribution systems. In *World Environmental and Water Resources Congress 2009: Great Rivers*, 1-10.

Bragalli, C., D’Ambrosio, C., Lee, J., Lodi, A., & Toth, P. (2012). On the optimal design of water distribution networks: a practical MINLP approach. *Optimization and Engineering*, 13(2), 219-246.

Dewis, N., & Randall-Smith, M. (2005). Discolouration risk modelling. *Water Asset Management International*, 1(3), 16-18.

Diao, K., Sweetapple, C., Farmani, R., Fu, G., Ward, S., & Butler, D. (2016). Global resilience analysis of water distribution systems. *Water research*, 106, 383-393.

Giordani, I., & Archetti, F. (2017). Models and architectures for emergency management. Journal of Ambient Intelligence and Humanized Computing*,* 8, 1–8

Giustolisi, O., Kapelan, Z., & Savic, D. (2008). Algorithm for automatic detection of topological changes in water distribution networks. *Journal of Hydraulic Engineering,* 134(4), 435-446.

Giustolisi, O., & Savic, D. (2010). Identification of segments and optimal isolation valve system design in water distribution networks. *Urban Water Journal*, 7(1), 1-15.

Godschalk, D. R., & Brower, D. J. (1985). Mitigation strategies and integrated emergency management. *Public Administration Review*, 45, 64-71.

Gonçalves, G. M., Gouveia, L., & Pato, M. V. (2014). An improved decomposition-based heuristic to design a water distribution network for an irrigation system. *Annals of Operations Research*, 219(1), 141-167.

Gupta, R., & Bhave, PR. (1996). Comparison of Methods for Predicting Deficient Network Performance. *Journal of Water Resources Planning and Management,* 122(3), 214-217.

Halhal, D., Walters, G. A., Ouazar, D., & Savic, D. A. (1997). Water network rehabilitation with structured messy genetic algorithm. *Journal of water resources planning and management*, 123(3), 137-146.

Hall, D., & Llinas, J. (2001). *Multisensor data fusion.* CRC press.

Higham, D. J., & Higham, N. J. (2016). *MATLAB guide*. Society for Industrial and Applied Mathematics.

ILOG, I. (2002). *CPLEX User's Manual 8.0.* ILOG.

Jeong, H. S., Qiao, J., Abraham, D. M., Lawley, M., Richard, J. P., & Yih, Y. (2006). Minimizing the consequences of intentional attack on water infrastructure. *Computer‐Aided Civil and Infrastructure Engineering,* 21(2), 79-92.

Jeong, H. S., & Abraham, D. M. (2009). Water rationing model for consequence minimization of water infrastructure destruction. *Journal of Water Resources Planning and Management,* 135(2), 80-89.

Jung, D., Kang, D., Liu, J., & Lansey, K. (2015). Improving the rapidity of responses to pipe burst in water distribution systems: a comparison of statistical process control methods. *Journal of Hydroinformatics*, 17(2), 307-328.

Jun, H., & Loganathan, G. V. (2007). Valve-controlled segments in water distribution systems. *Journal of Water Resources Planning and Management,* 133(2), 145-155.

Kang, D., & Lansey, K. (2012). Revisiting optimal water-distribution system design: issues and a heuristic hierarchical approach. *Journal of Water resources planning and management*, 138(3), 208-217.

Kao, J. J., & Li, P. H. (2007). A segment-based optimization model for water pipeline replacement. *Journal (American Water Works Association),* 99(7), 83-95.

Kapelan, Z., Giustolisi, O., & Savić, D. A. (2006). Risk assessment of water supply interruptions due to mechanical pipe failures. In *Proceedings of the Combined International Conference of Computing and Control for the Water Industry, CCWI2007 and Sustainable Urban Water Management, SUWM2007*, (2003), 1-5.

Kapelan, Z., Savic, D., & Mahmoud, H. (2017). A response methodology for reducing impacts of failure events in water distribution networks. *Procedia Eng,* 186, 218-227.

Keedwell, E., & Khu, S. T. (2006). A novel evolutionary meta-heuristic for the multi-objective optimization of real-world water distribution networks. *Engineering Optimization,* 38(03), 319-333.

Klein, L. A. (2004). *Sensor and data fusion: a tool for information assessment and decision making*, 138, *Spie Press*

Kumar, A., Kansal, M. L., Arora, G., Ostfeld, A., & Kessler, A. (1999). Detecting accidental contaminations in municipal water networks. *Journal of Water Resources Planning and Management*, 125(5), 308-310.

Laucelli, D., Romano, M., Savić, D., & Giustolisi, O. (2016). Detecting anomalies in water distribution networks using EPR modelling paradigm. *Journal of Hydroinformatics,* 18(3), 409-427.

McLoughlin, D. (1985). A framework for integrated emergency management. *Public Administration Review*, 45, 165-172.

Mahmoud, H. A., Kapelan, Z., & Savić, D. (2018). Real-Time Operational Response Methodology for Reducing Failure Impacts in Water Distribution Systems. *Journal of Water Resources Planning and Management*, 144(7), 04018029.

Marchi, A., Salomons, E., Ostfeld, A., Kapelan, Z., Simpson, A.R., Zecchin, A.C., Maier, H.R., Wu, Z.Y., Elsayed, S.M., Song, Y. and Walski, T. (2014). Battle of the water networks II. *Journal of water resources planning and management,* 140(7), 04014009.

Michaud, D., & Apostolakis, G. E. (2006). Methodology for ranking the elements of water-supply networks. *Journal of infrastructure systems*, 12(4), 230-242.

Nayak, M. A., & Turnquist, M. A. (2016). Optimal recovery from disruptions in water distribution networks. *Computer‐Aided Civil and Infrastructure Engineering*, 31(8), 566-579.

Ostfeld, A., & Salomons, E. (2004). Optimal layout of early warning detection stations for water distribution systems security. *Journal of Water Resources Planning and Management,* 130(5), 377-385.

Paez, D., Filion, Y., Castro-Gama, Quintiliani, C., Santopietro, S., Butler, D., Farmani, R., Fu, G., Meng, F., Sweetapple, C., Diao, K., Huang, Y., Ulanicki, B., Zhang, Q., Zheng, F., Abraham, E., Deuerlein, J., Gilbert, D., Piller, O., Balut, A., Brodziak, R., Bylka, J., Zakrzewski, P., Cai, J., Chenhao, O., Jinliang, G., Shiyuan, H., Yuanzhe, L., Mahmoud, H.A., Nikoloudi, E., Romano, M., Sophocleous, S., Woodward, K., Creaco, E., Di Nardo, A., Di Natale, M., Santonastaso, G.F., Bibok, A., Aguilar, A., Cuero, P., Gonzalez, S., Muñoz, S., Pérez, J., Posada, A., Robles, J., Salcedo, C., Vargas, K., Franchini, M., Galelli, S., Hoon Kim, J., Iglesias-Rey, P., Kapelan, Z., Saldarriaga, J., Savic, D., & Walski, T., (2020). The Battle of Post-Disaster Response and Restoration (BPDRR). *Journal of Water Resources Planning and Management*, 146(8), 04020067.

Preis, A., & Ostfeld, A. (2008). Multiobjective contaminant response modeling or water distribution systems security. *Journal of Hydroinformatics,* 10 (4), 267.

Petris, S., Georgoulis, C., Soldatos, J., Giordani, I., Sormani, R., & Djordjevic, D. (2014). Predicting terroristic attacks in urban environments: an internet-of-things approach. *International Journal of Security and Its Applications*, 8(4), 195-218.

Puust, R., Kapelan, Z., Savic, D. A., & Koppel, T. (2010). A review of methods for leakage management in pipe networks. *Urban Water Journal*, 7(1), 25-45.

Qi, Z., Zheng, F., Guo, D., Zhang, T., Shao, Y., Yu, T., Yu, T., Zhang, K. & Maier, H. R. (2018). A comprehensive framework to evaluate hydraulic and water quality impacts of pipe breaks on water distribution systems. *Water Resources Research*, 54(10), 8174-8195.

Romano, M., Kapelan, Z., & Savić, D. A. (2010). Real-time leak detection in water distribution systems. In *Water Distribution Systems Analysis* 2010, 1074-1082.

Romano, M., Kapelan, Z., & Savić, D. A. (2011). Burst detection and location in water distribution systems. In *World Environmental and Water Resources Congress* 2011: Bearing Knowledge for Sustainability, 1-10.

Rossman, L. A. (2000). *EPANET 2: users manual*.

Todini, E. (2003). A more realistic approach to the extended period simulation of water distribution networks. *Advances in water supply management*, 173-184.

Tolson, B. A., Asadzadeh, M., Maier, H. R., & Zecchin, A. (2009). Hybrid discrete dynamically dimensioned search (HD-DDS) algorithm for water distribution system design optimization. *Water Resources Research*, 45(12).

Turner, J. P., Qiao, J., Lawley, M., Richard, J. P., & Abraham, D. M. (2012). Mitigating shortage and distribution costs in damaged water networks. *Socio-Economic Planning Sciences*, 46(4), 315-326.

Tveiten, C. K., Albrechtsen, E., Wærø, I., & Wahl, A. M. (2012). Building resilience into emergency management. *Safety science*, 50(10), 1960-1966.

Venkatasubramanian, V., Rengaswamy, R., Yin, K., & Kavuri, S. N. (2003). A review of process fault detection and diagnosis: Part I: Quantitative model-based methods. *Computers & chemical engineering*, 27(3), 293-311.

Vamvakeridou-Lyroudia, L. S., Bicik, J., Morley, M., Savic, D., & Kapelan, Z. (2010). A Real-Time Intervention Management Model for Reducing Impacts Due to Pipe Isolation in Water Distribution Systems. In *Water Distribution Systems Analysis* 2010, 209-221.

Wagner, J. M., Shamir, U., & Marks, D. H. (1988). Water distribution reliability: simulation methods. *Journal of water resources planning and management*, 114(3), 276-294.

Walski, T. M., & Pelliccia, A. (1982). Economic analysis of water main breaks. *Journal-American Water Works Association*, 74(3), 140-147.

Walski, T. (2015). Can real-time modelling be useful for emergency planning and response?. In *World Environmental and Water Resources Congress* 2015, 685-695.

Walski, T. M., & Parrod, P. (2018). How utilities can improve every phase of emergency preparedness by leveraging data and hydraulic modelling capabilities. Retrieved from https://prod-bentleycdn.azureedge.net/-/media/files/documents/ebooks/ebook_emergency_planning_water_utilities_en.pdf?la=en&modified=20191122163043 [access 26/05/2021].

Wang, Q., M. Guidolin, D. Savic, & Z. Kapelan. (2013). Two-objective design of enchmark problems of a water distribution system via MOEAs: Towards the best-known approximation of the true Pareto front. *Journal of water resources planning and management*, 139 (3): 554–564.

Zhang, Q., Zheng, F., Chen, Q., Kapelan, Z., Diao, K., Zhang, K., & Huang, Y. (2020). Improving the Resilience of Postdisaster Water Distribution Systems Using Dynamic Optimization Framework. *Journal of Water Resources Planning and Management*, 146(2), 04019075.

Zheng, F., Simpson, A. R., & Zecchin, A. C. (2014). Coupled binary linear programming–differential evolution algorithm approach for water distribution system optimization. *Journal of Water Resources Planning and Management*, 140(5), 585-597.